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LEAN MIXTURES OF PROPANE AS A FUEL FOR INTERNAL COMBUSTION ENGINES

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, "LEAN MIXTURES OF PROPANE AS A FUEL FOR INTERNAL COMBUSTION ENGINES", submitted by GERALD ROY POND in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The performance of a single-cylinder, low speed, spark ignition, internal combustion engine has been studied using lean (i.e. air-rich) mixtures of propane as the fuel. The power output and thermal efficiencies have been determined at various compression ratios and fuel-air ratios. A comparison is also made with the engine when burning gasoline.

Maximum operating fuel economy is obtained at a fuel-air ratio of 0.04 lb. of propane per lb. of air, regardless of the compression ratio. It is also shown that the overall performance of an engine may be improved by burning propane as the fuel at a higher compression ratio than burning gasoline at a lower CR.

A theoretical analysis is also shown for obtaining "cycle" temperatures, indicated thermal efficiency and brake mean effective pressure.

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NOMENCLATURE

I.C.	Internal combustion
L.P.	Liquified petroleum
P	Pressure
V	Volume
T	Temperature
S	Entropy
Net W	Net work
Q_{in}	Heat in
Q_{out}	Heat out
m	Mass
C_p	Specific Heat at constant pressure
C_v	Specific Heat at constant volume
B.T.U.	British Thermal Units
η	Thermal efficiency
k	Ratio of specific heats
CR	Compression ratio
C_3H_8	Propane gas
O_2	Oxygen
N_2	Nitrogen
CO_2	Carbon Dioxide
CO	Cargon Monoxide
H_2O	Water Vapor
f	Fraction of residual gases remaining in the engine cylinder

U	Internal energy
H	Enthalpy
J	Conversion factor (778 ft-lb/BTU)
M	No. of moles
R	Universal Gas Constant (1545 ft-lb/lb-mole °R or 1.986 BTU/lb-mole °R)
ln	Logarithm to base e
x	Fraction of CO_2 dissociated
y	Fraction of H_2O "
G	Gibb's function
a	Moles of constituent A
b	Moles of constituent B
c	Moles of constituent C
d	Moles of constituent D
K_p	Pressure equilibrium constant
CE	Chemical energy
L.H.V.	Lower Heating Value of the fuel
u	Energy per mole
Φ_p	$m \int \frac{C_p dt}{T}$
m.e.p.	Mean effective pressure
r.p.m.	Revolutions per minute
S.A.E.	Society of Automotive Engineers
in.	Inches
Hg.	Mercury
°F	Degrees Fahrenheit

CF	Correction factor
Bar. Pres.	Barometric pressure
P_t	Total gas pressure
P_{sat}	Saturation pressure of water
T_{st}	Standard temperature (520°R)
BHP	Brake Horsepower
FHP	Friction Horsepower
IHP	Indicated Horsepower
CIHP	Corrected Indicated Horsepower (to S.A.E. Standard atmosphere)
CBHP	Corrected Brake Horsepower
Mech. Eff.	Mechanical efficiency
IMEP	Indicated Mean Effective Pressure
C	Orifice coefficient

CHAPTER I

INTRODUCTION

The fundamental problem considered in this investigation is the experimental determination of the effects of lean fuel-air ratios of gaseous propane (C_3H_8) when used as a fuel in a spark ignition four-cycle internal combustion engine.

1.1 HISTORY

The spark ignition four-cycle reciprocating internal combustion engine cycle is usually referred to as the Otto cycle, after N.A. Otto who is believed to have made the first successful internal combustion engine in about 1876.

A detailed explanation of the ideal Otto cycle and deviations from the ideal cycle are given in Chapter II.

1.1-1 Theoretical Cycles

Goodenough and Baker [1]* improved the understanding of internal-combustion engine analysis by considering actual mixtures of gasoline, clearance gases, variable

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* Numbers in square parenthesis designate References on page 56 .

specific heats and chemical equilibrium. Keenan and Kaye [2] prepared a set of highly accurate gas tables giving the thermodynamic properties of air and the combustion products of octane for fuel-air ratios of 25 and 50 percent of air for complete combustion at low temperatures i.e. they did not consider the dissociation of CO_2 and H_2O. Hottel, Williams and Satterfield [3] presented a series of charts for hydrocarbon-air combustion. Charts are given for fuel expressed as C_nH_{2n} for six fuel-air ratios, ranging from 80 percent to 150 percent required fuel.

A theoretical analysis, using propane as the fuel is presented in Chapter II.

1.1-2 Experimental Work

During the past several decades numerous experimental analyses have been conducted on spark-ignition internal combustion engines, using various fuels, but mainly gasoline, the most commonly used fuel in a practical engine. The prime objective of any engine is power output and since this is in direct proportion to the number of cylinders, mean effective pressures, length of stroke, area of cylinder and number of revolutions per minute, an increase in any one of these for a particular fuel will result in a power increase. Practical considerations however limit the number of cylinders and size of cylinders. Increasing

the speed will increase the power output, up to an optimum value. However, prior to this the effect of speed increase has been to cause the efficiency to be reduced. The greatest possibility for increase of horsepower per unit of engine weight lies in increasing the mean effective pressure.

The most obvious way to increase the mean effective pressure is to increase the compression ratio of the engine. For a particular fuel, however, there is a maximum compression ratio above which the fuel will detonate (Engine Knock). Detonation results in a loss of power and if severe, the engine will be damaged. Many factors determine when a particular fuel will knock. Some of these factors are combustion chamber design, engine speed, spark timing, cylinder temperature, air-fuel ratio and air-fuel mixture temperature. Gasoline with knock inhibitors are now available which will allow engines to operate without knock at a higher compression ratio than if the gasoline were used without the inhibitor. Many investigations have been conducted regarding Engine Knock [4, 5, 6, 7].

Propane has a higher detonation resistance than all but the most expensive aviation gasoline. Propane also has the other characteristics necessary for a fuel in an I.C. engine i.e. adequate volatility without preheating, low sulphur content, has high heating value,

readily available at an economical cost, and the added advantage over gasoline in that its combustion is more complete [8]. Thus carbon deposits in the combustion chamber, and on the valves and piston head are notably reduced resulting in less dirty engine oil, resulting in fewer oil changes and less engine wear. There is also a reduction in the noxious exhaust odors, smoke and soot. Another advantage of propane is that it has a slow rate of flame travel during combustion, resulting in a decrease in peak pressure but resulting in an increase in mean effective pressure.

Operating variables such as spark advance, exhaust pressure, inlet pressure, inlet mixture temperature also have an influence on the mean effective pressure and the engine efficiency. A very thorough comparison of the effects of these variables is shown in Taylor [9].

The heating value of a fuel is not in direct proportion to the power output which can be obtained from the use of that fuel in a particular engine because of other factors which affect the power output. The heating value is, however, a direct measure of the quantity of fuel required; the higher the heat value the less fuel needed to do the same work. Propane has a slightly higher heating value per pound than gasoline but a lower value if compared on a volume basis.

Adams and Boldt [10] conducted extensive tests on three industrial engines, including one engine at three compression ratios using gasoline and liquified petroleum gas (Butane-propane). They found that at a given compression ratio, the engines developed 3-1/2 - 5% less power at high speeds on L.P.-gas than on gasoline. However compared to gasoline the L.P.-gas reduced brake specific fuel consumption on a mass basis up to 12% at low speeds. At high speeds fuel consumption was reduced by 0 - 9%. On a volume basis, the L.P. gas consumption increased due to the lower specific weight of the L.P.-gas. They also found that increasing the compression ratio from 7.5 to 11.5 increased the power 12% and reduced the brake specific fuel consumption by 11%.

Because of the certain advantages of propane as a fuel for internal combustion engines it is the purpose of this thesis to obtain data on an engine operating at maximum economy fuel-air ratio. Although this fuel-air ratio is at a lower than maximum power such information is necessary and of importance for vehicles when operating at cruising speed and is also very important to the designer and owner of stationary engines wishing to operate at maximum economy over an extended period of time.

CHAPTER II

THEORETICAL ANALYSIS

2.1 GOVERNING EQUATIONS

2.1-1 Otto Air-Standard Cycle

The simplest and crudest analysis of the Otto cycle considers the working medium as air or at least a gas having the properties of air. It is further assumed that the air has a constant specific heat.

This cycle is shown on the P-V and T-S diagrams of Fig. 2.1.

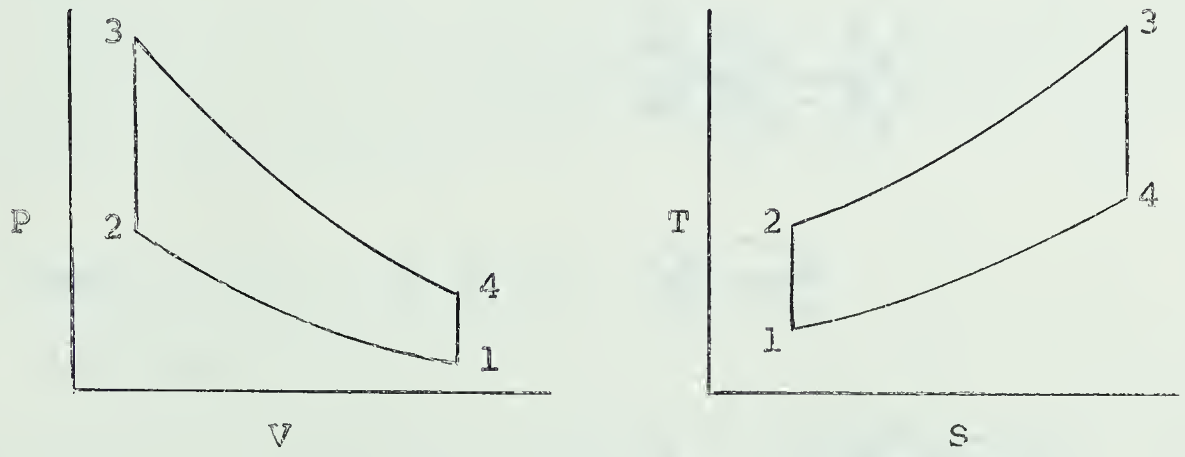


FIG. 2.1 OTTO CYCLE

The medium is compressed reversibly and adiabatically, i.e. isentropically, process 1-2. Heat is added at constant volume, process 2-3, while the piston is momentarily at rest at "top-dead center". Ignition occurs prior to point 3 in the actual engine. Isentropic expansion takes place, process 3-4, and process 4-1 is the rejection of heat while the piston is returning to its initial position at "bottom-dead center".

From the First Law of Thermodynamics for a closed system and assuming no changes in kinetic, potential or chemical energies and assuming adiabatic compression and expansion the net work of the system may be obtained from:

$$\text{Net } W = Q_{in} - Q_{out}$$

where $Q_{in} = mc_v\,(T_3 - T_2)$ and $Q_{out} = mc_v\,(T_4 - T_1)$

The thermal efficiency $(\eta) = \dfrac{\text{net } W}{Q_{in}}$

$$\text{therefore} \qquad \eta = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \tag{2.1}$$

$$= 1 - \frac{mc_v(T_4 - T_1)}{mc_v(T_3 - T_2)}$$

$$\text{so} \qquad \eta = 1 - \frac{T_4 - T_1}{T_3 - T_2} \tag{2.2}$$

$$= 1 - \frac{T_1}{T_2} \cdot \left(\frac{T_4/T_1 - 1}{T_3/T_2 - 1}\right)$$

But from isentropic relationships

$$\frac{T_4}{T_3} = \left(\frac{V_3}{V_4}\right)^{k-1} = \left(\frac{V_2}{V_1}\right)^{k-1} = \frac{T_1}{T_2}$$

$$\therefore \qquad \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

so $$\eta = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{V_2}{V_1}\right)^{k-1}$$

But $$\frac{V_1}{V_2} = \frac{V_4}{V_3} = \text{CR (Compression ratio)}.$$

$$\therefore \quad \eta = 1 - CR^{1-k} \qquad (2.3)$$

Thus in the air-standard Otto cycle the thermal efficiency is a function of only the compression ratio and the efficiency may be increased by increasing the compression ratio. Although the thermal efficiency will increase to a maximum value of one as CR increases, the rate of increase of η decreases as CR increases, and any increase is practically insignificant as the CR approaches 15 or 20.

2.1-2 Otto Fuel-Air Cycle

The spark-ignition engine deviates from the air-standard cycle in many ways. Some of the more important ways are as follows:

1. The medium consists of a mixture of fuel, air and residual gases.
2. The specific heats of the individual gases are different and vary with temperature.
3. The combustion process replaces the heat transfer process. Combustion takes time and is thus initiated before top-dead center.

4. After combustion, i.e. during adiabatic expansion and exhaust, the medium is no longer a mixture of fuel and air but air and products of combustion.
5. The reaction may not be complete.

The fuel-air cycle is an idealized thermodynamic process resembling what is occurring in an "ideal" engine because in a real engine the process is not cyclic in the thermodynamic sense.

Further deviations take place in the actual engine due to:

1. The inlet and exhaust processes will result in a pressure drop through the valves thus resulting in a loss of work.
2. The piston must do work on the mixture to get it out of the cylinder and this is more than the work done in the cylinder by the mixture at intake, resulting in a net loss of work.
3. Heat transfer is involved, so the compression and expansion processes are not isentropic, as assumed.

Fig. 2.2 illustrates the deviation of the actual cycle from the ideal cycle as it affects the P-V diagram.

2.2 ANALYSIS USING PROPANE

The reaction equation for propane reacting with the

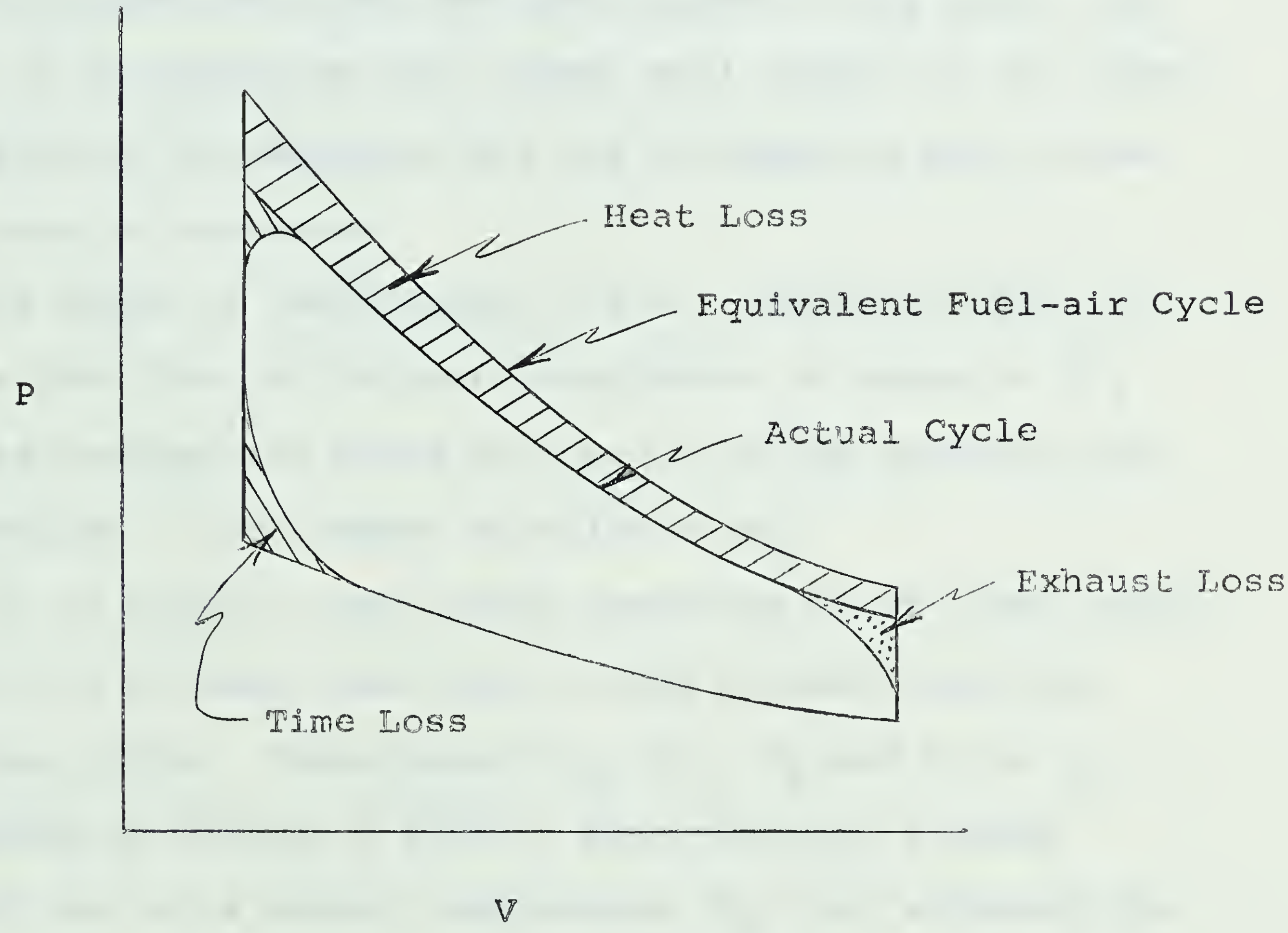


FIG. 2.2 ACTUAL FUEL-AIR CYCLE LOSSES

correct amount of air for complete combustion i.e. stoichiometric air-fuel ratio, is:

$$C_3H_8 + 5\ O_2 + 3.76(5)N_2 \rightleftharpoons 3CO_2 + 4H_2O + 3.76(5)N_2 \qquad (2.2\text{-}1)$$

(assuming air 21% oxygen and 79% nitrogen by volume, where the % nitrogen includes the inert gases in the air). If there is an excess of air, oxygen will appear on the right hand side of the equation and the nitrogen on both sides will also be increased.

If there is insufficient air for complete combustion i.e. a rich fuel-air mixture the number of moles of CO_2 will be reduced and there will be CO in the products and a reduction in the number of moles of N_2.

In an engine, even though operating on an ideal cycle, there will be some gases left in the cylinder from the previous cycle. These gases CO_2, H_2O, N_2 and CO or O_2, depending on whether a rich or lean mixture is being burned, are at a higher temperature (T_5) and although the volume is small (approximately 3% of V_5) there is an appreciable increase in energy and temperature of the incoming mixture when mixed with the residual gases.

Assuming 100% air and "f" as the fraction of residual gases remaining in the cylinder the reaction equation 2.2-1 now becomes:

$$C_3H_8 + 5\ O_2 + 18.8N_2 + f(3CO_2 + 4H_2O + 18.8N_2) \rightleftharpoons$$

$$3(1 + f)CO_2 + 4(1 + f)H_2O + 18.8(1 + f)N_2 \qquad (2.2\text{-}2)$$

The temperature of the incoming fuel-air mixture may be measured and thus the enthalpy obtained. However, the temperature of the residual gases and "f" have to be estimated and later confirmed, i.e. a trial solution.

The internal energy at T_1 may be expressed as:

$$U_1 = H_{charge} + U_{Res.\ gas} - \frac{P_1(V_1 - V_o)}{J}$$

but $PV = MRT \qquad \therefore \quad P_1 = \frac{MRT_1}{V_1}$

and $V_o = V_2$

$$\therefore \quad \frac{P_1(V_1 - V_o)}{J} = \frac{M(1545)}{778} \frac{T_1}{V_1} \left(V_1 - V_o\right)$$

$$= M(1.986)T_1 \left(1 - \frac{V_o}{V_1}\right)$$

$$= M(1.986)T_1 \left(1 - \frac{1}{CR}\right)$$

where CR is the compression ratio.

$$\therefore U_1 = H_{fuel} + H_{O_2} + H_{N_2} + U_{res.gas} - M(1.986)T_1\left(1 - \frac{1}{CR}\right) \tag{2.2-3}$$

At an assumed temperature T_1, U_1 can thus be obtained. Then considering the entire mixture at T_1, the sum of the internal energies of the gases can be obtained from:

$$U_1 = U_{fuel} + U_{O_2} + U_{N_2} + U_{CO_2} + U_{H_2O}$$

This process is repeated at various T_1's until both calculated U_1's are of the same value. The value of T thus obtained is taken as T_1.

Isentropic compression from T_1 to T_2 gives a means of obtaining T_2.

$$S_2 - S_1 = 0 = \sum MC_v \ln \frac{T_2}{T_1} + \sum MR \ln \frac{V_2}{V_1}$$

$$\text{i.e. } \sum Mc_v \ln \frac{T_2}{T_1} = -\sum MR \ln \frac{V_2}{V_1} = \sum MR \ln \frac{V_1}{V_2} = \sum MR \ln CR$$

Various values of T_2 are assumed until

$$\sum Mc_v \ln \frac{T_2}{T_1} = \left(\sum M\right) R \ln CR \tag{2.2-4}$$

The energy at T_2 is then calculated from

$$U_2 = U_{C_3H_8} + U_{O_2} + U_{N_2} + U_{CO_2} + U_{H_2O}$$

U and S are calculated using Cp and Cv as a function of temperature [11] or from the tables based on Cp and Cv as functions of temperature [12], (Table datum is $520^{\circ}R$).

The process 2-3 of Fig. 2.1 represents the combustion of the fuel at constant volume. In the ideal case this process is assumed to be adiabatic and the gas mixture is in equilibrium when state 3 is reached.

The mixture at the high temperature of T_3 will contain unburned CO and H_2 i.e. the CO_2 and H_2O dissociates into CO and O_2 and H_2 and O_2, respectively.

If x and y represent the degrees of dissociation of CO_2 and H_2O, respectively, the reaction equation, 2.2-2 can be written as:

$$C_3H_8 + 5O_2 + 18.8N_2 + f(3CO_2 + 4H_2O + 18.8N_2) \rightleftharpoons$$

$$3(1+f)(1-x)\ CO_2 + 3(1+f)(x)CO + 4(1+f)(1-y)H_2O + 4(1+f)(y)H_2$$

$$+ (1+f)\left(\frac{3x}{2} + \frac{4y}{2}\right) O_2 + (1+f)\ (18.8)N_2 \qquad (2.2\text{-}5)$$

The criteria for chemical equilibrium is that the Gibbs function (Gibbs free energy) for the system must be a minimum. The Gibbs function is defined as:

$$G = H - TS$$

By differentiating and substituting it can be shown that

$$dG = VdP - SdT$$

At the final approach to equilibrium the process may be considered isothermal, i.e. $dT = 0$.

$$\therefore \quad dG = VdP$$

Assuming a perfect gas relationship: $V = \frac{RT}{P}$

$$\therefore \quad dG = RT \frac{dP}{P}$$

Integrating this equation gives:

$$G_2 - G_1 = \Delta G = RT \ln (P_2/P_1).$$

For the reaction $aA + bB \rightleftharpoons cC + dD$

$$\Delta G_2 - \Delta G_1 = \Delta G_C + \Delta G_D - G_A - \Delta G_B$$

$$= cRT \ln (P_2/P_1)_C + dRT \ln (P_2/P_1)_D$$

$$- aRT \ln (P_2/P_1)_A - bRT \ln (P_2/P_1)_B$$

$$= RT \ln \frac{(P_{2C})^c \ (P_{2D})^d}{(P_{2A})^a \ (P_{2B})^b} - RT \ln \frac{(P_{1C})^c \ (P_{1D})^d}{(P_{1A})^a \ (P_{1B})^b}$$

Arbitrary values may be assigned so that the last term has a value of zero.

i.e. $\quad P_{1C} = P_{1D} = P_{1A} = P_{1B} = 1$ atmosphere.

$$\therefore \quad \Delta G_2' - \Delta G_1' = RT \ln \frac{(P_{2C})^c (P_{2D})^d}{(P_{2A})^a (P_{2B})^b}$$

Considering point 2 as the condition at equilibrium where there is no change in free energy, $\Delta G_2'$ becomes zero and $\Delta G_1'$ becomes ΔG^0

$$\therefore \quad -\Delta G^0 = RT \ln \frac{(P_C)^c (P_D)^d}{(P_A)^a (P_B)^b}$$

or

$$e^{-\frac{\Delta G^0}{RT}} = \frac{(P_C)^c (P_D)^d}{(P_A)^a (P_B)^b} = K_p$$

where K_p represents the pressure equilibrium constant. Since the partial pressures of a mixture of gases may be assumed proportional to the mole fractions

$$K_p = \frac{(C)^c (D)^d}{(A)^a (B)^b} \tag{2.2-6}$$

K_p is a function of temperature and values of K_p for various gases are tabulated [13]. Since the deviation of the actual gas from the ideal gas is slight, the compressibility correction factor Z may be taken as 1 in the range of temperatures and pressures encountered in combustion.

$$\therefore \quad K = K_p$$

Considering the dissociation of $2CO_2$ into $2CO$ and O_2,

$$K_{CO_2} = \frac{\left[CO\right]^2 \left[O_2\right]}{\left[CO\right]^2} \qquad (2.2\text{-}7)$$

Substituting for the values of the number of moles, from equation 2.2-5, equation 2.2-7 becomes:

$$K_{CO_2} = \frac{\left[\frac{3(1+f)(x)P_3}{M_3}\right]^2 \left[\frac{3(1+f)x + 4(1+f)y}{2M_3}\right] P_3}{\left[\frac{3(1+f)(1-x)}{M_3} P_3\right]^2}$$

$$= \left[\frac{x}{1-x}\right]^2 \left[\frac{3}{2}(1+f)x + \frac{4}{2}(1+f)y\right] \frac{P_3}{M_3}$$

but $\quad \frac{P_3}{M_3} = \frac{RT_3}{V_3}$ where $R = \frac{P_2V_2}{M_2T_2}$ and $V_2 = V_3$

$$\therefore \quad K_{CO_2} = \left[\frac{x}{1-x}\right]^2 \left[\frac{3}{2}(1+f)x + \frac{4}{2}(1+f)y\right] \frac{P_2T_3}{M_2T_2} \qquad (2.2\text{-}8)$$

The equilibrium constant for the dissociation of $2H_2O$ may be expressed in the same manner.

For reasons to be explained later it is advantageous

to determine the water-gas equilibrium constant K_{WG} rather than K_{H_2O}. Considering the two equations:

$$2CO_2 \rightleftharpoons 2CO + O_2$$

$$2H_2O \rightleftharpoons 2H_2 + O_2$$

Subtraction gives

$$2CO_2 - 2H_2O \rightleftharpoons 2CO - 2H_2$$

or

$$H_2 + CO_2 \rightleftharpoons H_2O + CO$$

$$\therefore \quad K_{WG} = \frac{\left(P'_{CO}\right)\left(P'_{H_2O}\right)}{\left(P'_{CO_2}\right)\left(P'_{H_2}\right)} \tag{2.2-9}$$

In terms of x and y and mole fractions this equation becomes

$$K_{WG} = \frac{x(1-y)}{(1-x)y} \tag{2.2-10}$$

Values of K_{WG} at various temperatures are also tabulated [13].

Theoretically, the H_2, O_2 and N_2 will dissociate into their respective atoms and small amounts of OH, NO, NH_3 and CH_4 may form, but at high pressures as found in the Otto cycle, this dissociation is very slight and is neglected in this analysis.

T_3 may be obtained by using the first Law of Thermodynamics,

expressed as:

$$U_2 + CE_{fuel} = U_3$$

U_2 and the CE of the fuel are known. The CE is obtained from $CE + U_{O_2} + U_{fuel} = U_{CO_2} + U_{H_2}$ + Heating Value of fuel.

Heating Value of C_3H_8 = 878,749 BTU/mole [14].

$$U_3 = U_{CO_2} + U_{CO} + U_{H_2O} + U_{H_2} + U_{O_2} + U_{N_2}$$

$$= 3(1+f)(1-x)\, u_{CO_2} + 3(1+f)x\, u_{CO} +$$

$$4(1+f)y\, u_{H_2} + (1+f)\left(\frac{3x}{2} + \frac{4y}{2}\right) u_{O_2} + 18.8(1+f)u_{N_2} \tag{2.2-11}$$

T_3, x and y are yet unknown, therefore, this equation cannot be solved.

Considering equations 2.2-8, 2.2-10 and 2.2-11 there are three equations with five unknowns T_3, x, y and K_{WG} and K_{CO_2}, since the "u's" of equation 2.2-11 are all known functions of temperature. A trial solution is involved to obtain T_3. T_3 is assumed, and the internal energies of the various gases in equation 2.2-11 are obtained by using the equations $u = \int C_p dT$ where C_p is a function of temperature [11,12]. The x, y and numerical terms are added algebraically resulting in an equation of the form,

$$U_2 + CE_{C_3H_8} - \sum N_{terms} = x \sum x_{terms} + y \sum y_{terms}$$

Therefore y may be obtained in terms of x

i.e. $$y = \frac{\text{Number} - x \sum x_{terms}}{\sum y_{terms}} \qquad (2.2\text{-}12)$$

From equation 2.2-10, y can also be obtained in terms of x, as K_{WG} can now be obtained for the assumed value of T_3.

$$\therefore \quad y = \frac{x}{K_{WG} - x(K_{WG} - 1)} \qquad (2.2\text{-}13)$$

Equating equations 2.2-12 and 2.2-13 eliminates y and results in a quadratic equation in terms of x from which a value of x may be obtained. y may then be calculated from either equation 2.2-12 or equation 2.2-13. Using these values of x and y in equation 2.2-8 a value is obtained for K_{CO_2}. This procedure is repeated at various T_3's until K_{CO_2} calculated is approximately equal to K_{CO_2} as tabulated [13]. When various T_3's are obtained, the correct T_3, x and y may be obtained by linear interpolation or by graphical means, such that K_{CO_2} calculated equals K_{CO_2} from the tables.

Process 3-4 is assumed to be isentropic expansion, therefore $S_3 = S_4$. Knowing T_3, x_3 and y_3 the entropy at 3 may be calculated by the equation:

$$s_3 = \sum \phi - \sum MR \ln pp. + \frac{M_{CO} CE_{CO}}{T_3} + \frac{M_{H_2} \; CE_{H_2}}{T_3} \qquad (2.2\text{-}14)$$

where ϕ is $M \int \frac{C_p dt}{T}$ and pp is the partial pressure of the constituent gas.

The determination of T_4 again involves a trial solution since the degrees of dissociation of the CO_2 and H_2O cannot be determined until after T_4 is obtained. Assuming a value of T_4, K_{CO_2} and K_{WG} may be obtained from the tables. Using equation 2.2-13, y may be obtained in terms of x. Substituting in equation 2.2-8 results in

$$K_{CO_2} = \left(\frac{x}{1-x}\right)^2 \left[\frac{3}{2}\,(1+f)x + \frac{\frac{4}{2}\,(1+f)x}{K_{WG} - (K_{WG} - 1)x}\right] \frac{P_4}{M_4}$$

but $\frac{P_4}{M_4} = \frac{RT_4}{V_4} = \frac{RT_4}{V_1} = \frac{P_1 V_1}{M_1 T_1} \cdot \frac{T_4}{V_1} = \frac{T_4 (1.)}{M_1 T_1}$

since $P_1 = 1.$ atm.

therefore

$$K_{CO_2} = \left(\frac{x}{1-x}\right)^2 \left[\frac{3}{2}\,(1+f)x + \frac{\frac{4}{2}\,(1+f)x}{K_{WG} - (K_{WG} - 1)x}\right] \frac{T_4}{M_1 T_1} \qquad (2.2\text{-}15)$$

Various values of x are assumed and substituted until K_{CO_2} as calculated equals the value of K_{CO_2} obtained from

the tables.

Using the assumed value of T_4, x_4 and y_4 as obtained, the entropy at T_4 may be calculated by the equation

$$S_4 = \sum \phi - \sum MR \ln pp + \frac{M_{CO} \; CE_{CO}}{T_4} + \frac{M_{H_2} \; CE_{H_2}}{T_4}$$

If S_4 exceeds S_3, T_3 is assumed lower, and vice versa. The above procedure is repeated until $S_3 = S_4$, thus giving the temperature T_4.

At 4, the end of the expansion process, the exhaust valve opens and the combustion products escape from the cylinder and the pressure decreases to atmospheric pressure. The gases in the cylinder expand isentropically to atmospheric pressure. Some of these gases remain in the clearance space in the cylinder. Considering this as condition 5 it is possible to calculate V_5, and knowing V_2 check on the assumed value of "f" and also the assumed value of T_5. Since T_5 is in the order of 2200 °R it is reasonable to assume the amount of dissociation of CO_2 and H_2O is negligible.

For an assumed T_5 the entropy of 5 may be calculated using

$$S_5 = \sum \phi_5 - \sum MR \ln pp.$$

Various T_5's are assumed until a value is obtained which

results in $S_5 = S_3$.

The fraction of residual gas, $f = \frac{V_2}{V_5}$, may now be obtained

$$V_2 = \frac{V_1}{CR} = \frac{M_1 R T_1}{14.7(144)CR}$$

and

$$V_5 = \frac{M_5 R T_5}{14.7(144)}$$

therefore

$$f = \frac{V_2}{V_5} = \frac{T_1(M_1)}{CR(T_5)M_5} \qquad (2.2\text{-}16)$$

If T_5 and "f" differ greatly from the initially assumed values of "f" and T_5 the entire calculations must be repeated until there are negligible changes in "f" and T_5.

The thermal efficiency is defined as

$$\eta = \frac{\text{Net Work}}{\text{Heat Added}}$$

$$= \frac{(U_3 - U_4) - (U_2 - U_1)}{\text{Heat Value of Fuel}} \qquad (2.2\text{-}17)$$

The heat value of propane is taken as the lower heat value of 19929 BTU/lb [14]. Knowing the temperatures T_1, T_2, T_3 and T_4 the internal energies may be calculated and the thermal efficiencies obtained by equation 2.2-17.

The mean effective pressure may be obtained from

$$\text{m.e.p.} = \frac{\text{net work}}{\text{displacement}}$$

therefore $$\text{m.e.p.} = \frac{(U_3 - U_4) - (U_2 - U_1)}{(V_1 - V_2)\ 144} \qquad (2.2\text{-}16)$$

A sample calculation is given in Appendix A.

A computer programme in Fortran IV language was written to carry out the above calculations for various percentages of air, compression ratios, and various fuels. The computations were done on the IBM 7040-1401 system in the Department of Computing Science, University of Alberta. Appendix B shows this program. The results are plotted in Chapter IV. Iterations were continued until there was less than a 1° temperature variation in any particular assumed temperature or ½% variation in any other assumed value.

Convergence is illustrated by means of the table which follows. These results are at a compression ratio of 10. Results at other compression ratios showed similar effects.

Percent air	Thermal Efficiency		
	20% air Intervals	10% air Intervals	
		1% variation	½% variation
100	36.8	36.9	36.9
110		39.5	39.5
120	43.7	41.8	41.8
130		43.6	43.6
140	58.3	44.8	44.8
150		45.0	45.0
160	46.6	46.6	46.6
170		46.2	46.2
180	46.5	46.9	46.9
190		47.7	47.7
200	46.2	47.9	47.9

CHAPTER III

EXPERIMENTAL WORK

3.1 EQUIPMENT

The engine used in conducting these tests was an "ASTM-CFR-48 Engine" located in the Mechanical Engineering Laboratory of the University of Alberta. The engine is connected to a series wound D.C. motor capable of starting the engine and absorbing the power developed by it (dynamometer). The engine has a bore of 3.25 in., stroke of 4.50 in., variable spark adjustment and a variable, from 4 to 10, compression ratio. The standard CFR engine cooling system, evaporative cooling, was used to maintain the coolant temperature at 208°F (See Fig. 3-1).

The air flow into the air inlet surge tank was measured by means of an orifice and inclined manometer.

Gaseous propane was introduced into the air stream, at the throat of the carburetor, to ensure adequate mixing. The propane flow was measured by means of a "Precision" Wet Test Gas Meter, manufactured by Precision Scientific Co., placed in the propane gas line after the pressure reducer and before the engine carburetor. The meter capacity was 0.250 cu. ft. per revolution of the sweep dial, with a maximum pressure of 8 in. of water.

The combustion chamber mean temperature was obtained

by a chromel-alumel thermocouple, placed in the top of the cylinder, at the "knock-meter connection". The thermocouple readings were obtained on a Leeds and Northrup Millivolt potentiometer.

The time of runs, for the combustion of 0.500 cu. ft. of gas, and the number of revolutions per run were obtained on the timing unit on the control panel (see Fig. 3-2).

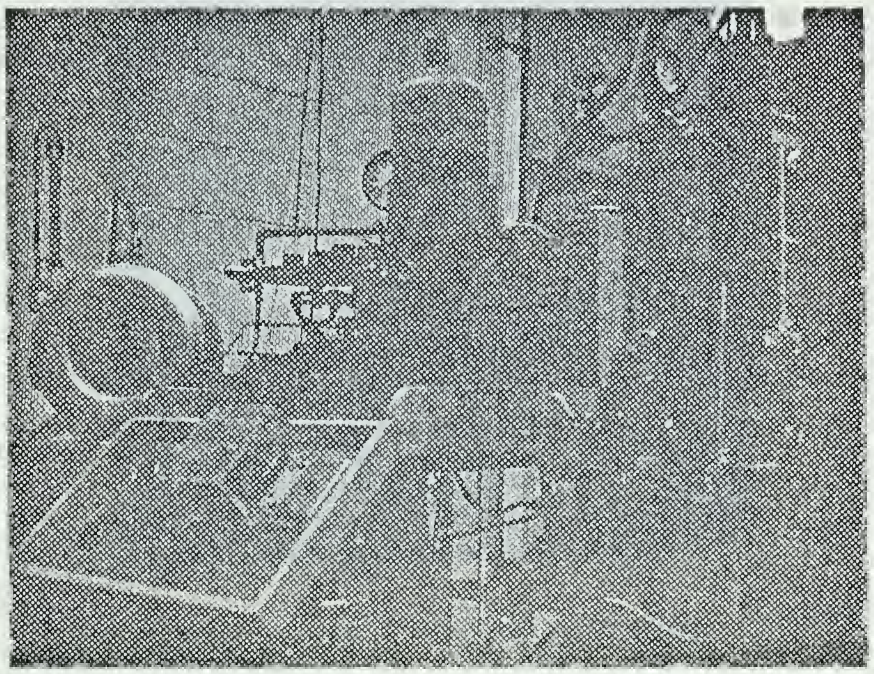
Exhaust gas analyses were obtained by means of a Hays Gas Analyzer (Orsat), capable of determining the percent by volume, of CO_2, O_2 and CO.

3.2 EXPERIMENTAL METHODS

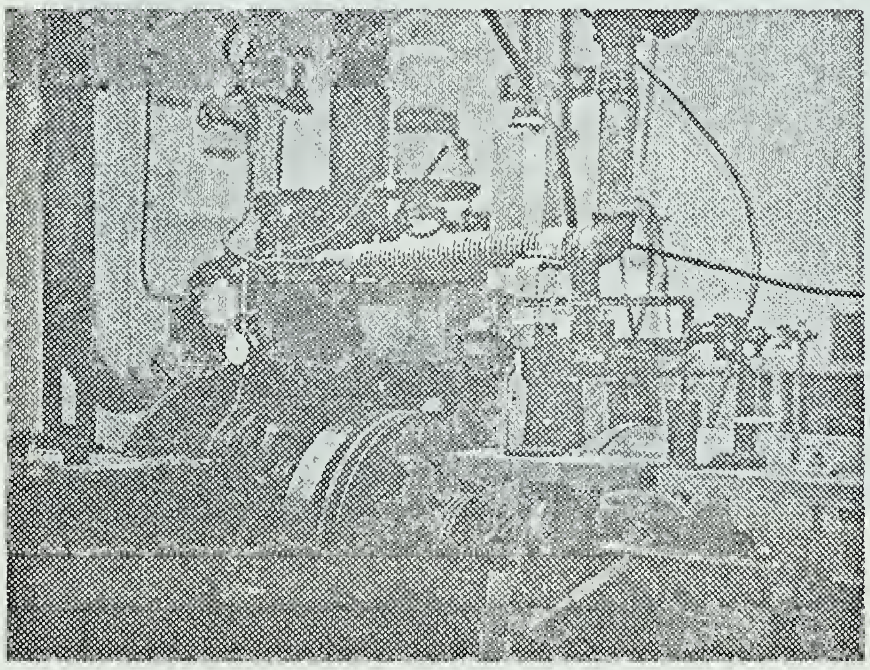
Initial tests were conducted with the engine as provided. Later tests were done with the engine exhaust valve replaced by a mild steel exhaust valve, manufactured locally, to determine the effects of oxidation, if any. No apparent changes occurred in the operation of the engine as a result of the changing of the exhaust valve. A photo of this valve showing the thermocouple wire is shown in Fig. 3.3.

3.2-1 Test Procedure

After preliminary testing, the engine oil was renewed and the micrometer gage, indicating the compression



Front View



Side View

FIG. 3-1 CFR-ENGINE AND TEST EQUIPMENT

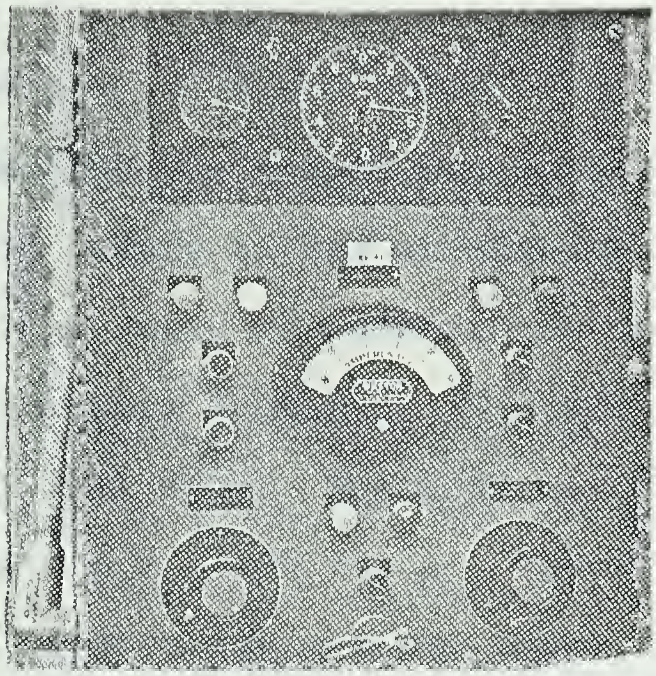


FIG. 3-2 CONTROL PANEL

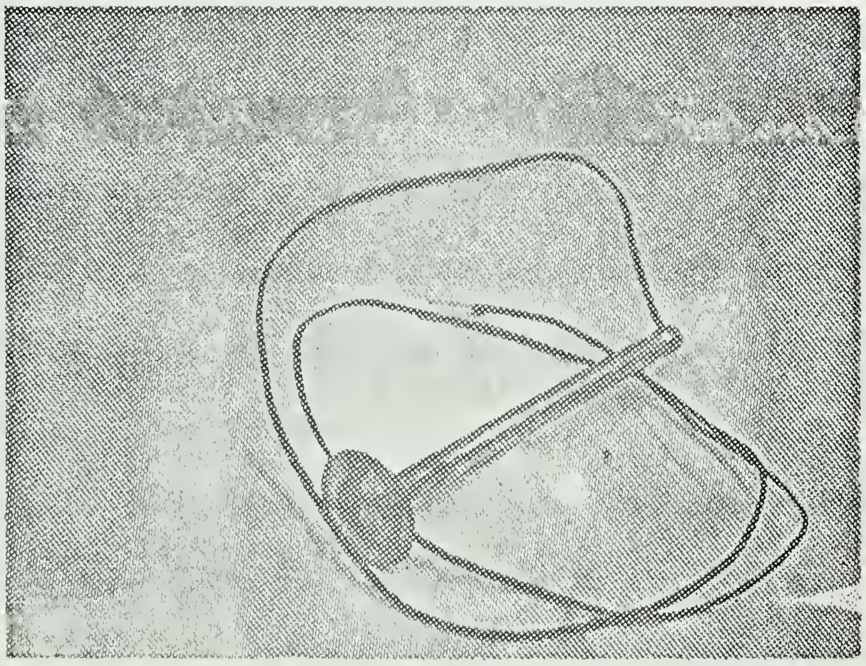


FIG. 3-3 MILD STEEL EXHAUST VALVE

ratio, was calibrated.

Prior to a test run the engine was operated for a considerable time to ensure it was at operating temperature. The compression ratio was set at the desired value and the gas pressure regulator adjusted to give the desired rate of fuel flow. The load was then adjusted to give the desired r.p.m. (600 for all tests). The spark was adjusted to give the maximum power output, indicated by the lifting of the load beam on the dynamometer. The speed was then re-adjusted and the spark re-adjusted again for maximum torque.

The throttle was run fully open and the fuel-air ratio varied by adjusting the gas flow rate only.

An exhaust gas sample was introduced into the gas analyzer at this time, and the timer initiated to record the time and number of engine revolutions for the burning of 0.500 cu. ft. of gas.

During the test run the exhaust gas was analyzed for CO_2, O_2 and CO and the following data recorded:

Test No.	Cooling Water Temperature
Oil Pressure	Barometric Pressure
Compression Ratio	Spark Angle
No. of Revolutions	Time
Fuel Temperature	Gas Meter Pressure

Air Temperature	Pressure of Air Manometer
Cylinder Temperature	% CO_2 by Volume
% O_2 by Volume	% CO by Volume
Dynamometer Load	

The above was repeated for a series of "runs" at the same compression ratio at different fuel flows. Immediately after a series of "runs" the engine was "motored" to determine the friction horsepower. A typical set of data is shown in Appendix C.

3.2-2 Calculations

1. In order to compensate for variations in ambient conditions a correction was made to refer all results affected by ambient conditions to the standard conditions adopted by S.A.E. i.e. atmospheric pressure of 29.00 in. Hg. and 85 °F. The correction factor is calculated by the following formula

$$CF = \frac{29.00}{\text{Bar. Pres.}} \sqrt{\frac{460 + T}{460 + 85}} \left[15 \right] \qquad (3.2\text{-}1)$$

2. Flow of Fuel

To determine the mass rate of flow of propane the following equations were used:

$$\text{Gas Pressure} = \text{ins. of } H_2O \times \frac{29.92}{33.899 \times 12} \text{ (ins. of Hg.)} \qquad (3.2\text{-}2)$$

Saturation Pressure of H_2O:

$$P_{sat} = \text{Sat. Pres.} + \frac{29.92}{14.696} \text{ (ins. Hg)} \qquad (3.2\text{-}3)$$

where Sat. Pres. was obtained from Steam Tables [16].

Total Pressure (P_T) = Bar. Pres. + Gas Pres. (ins. Hg)

$$\text{Volume (V)} = V_o \; \frac{P_o}{P_{st}} \times \frac{T_{st}}{T_o} \quad , \text{ from } [7].$$

$$= V_o \; \frac{(P_t - P_{sat})\ (460 + 60)}{29.92\ (460 + \text{Gas Temp.})} \quad (ft^3) \qquad (3.2\text{-}4)$$

Using the specific volume of propane at 60 °F and 1 atmosphere = 8.503 ft^3/lb [18] it is possible to calculate the weight of propane flowing per hour.

$$\text{Therefore, lbs. of } C_3H_8 \text{ per hour} = \frac{V \times 60}{8.503 \times \text{time}} \quad \text{(lbs/hr)} \qquad (3.2\text{-}5)$$

3. Torque

The torque developed by the engine was obtained from the product of the load on the dynamometer scales and the moment arm of the dynamometer (10.52 ins).

$$\text{Torque} = \frac{10.52}{12} \times \text{load} \quad \text{(ft. lbs)} \qquad (3.2\text{-}6$$

4. Brake Horsepower

$$BHP = \frac{2\pi(\text{Torque})\,r.p.m.}{33{,}000} \quad (H.P.) \qquad (3.2\text{-}7)$$

5. Friction Horsepower

$$FHP = 2\pi\left(\frac{10.52}{12}\right)\frac{(\text{Fr. Load})\,r.p.m.}{33{,}000} \quad (H.P.) \qquad (3.2\text{-}8)$$

6. Indicated Horsepower

$$IHP = BHP + FHP \quad (H.P.)$$

7. Corrected Indicated Horsepower

$$CIHP = CF \circ IHP \quad (H.P.)$$

8. Corrected Brake Horsepower

$$CBHP = CIHP - FHP \quad (H.P.)$$

9. Thermal Efficiency

The thermal efficiency is the ratio of the work out to the heat added, expressed as a percent. Since this combustion process is at constant volume and the H_2O formed is in the gaseous state, the constant volume Lower Heating Value was used as the available heat. L.H.V = 19,929 BTU/lb. [12].

Indicated Thermal Efficiency $(\eta) = \frac{\text{CIHP}(2545)100}{\text{lb/hr.}(19{,}929)}$ (%)

Brake Thermal Efficiency $(\eta_B) = \frac{\text{CBHP}(2545)100}{\text{lb/hr.}(19{,}929)}$ (%)

10. Mechanical Efficiency

$$\text{Mech. eff} = \frac{\text{CBHP}}{\text{CIHP}} \times 100 \quad (\%)$$

11. Fuel per Indicated Horsepower

$$\text{lb. fuel/Hr/CIHP} = \frac{\text{lb.}}{\text{CIHP-Hr.}}$$

12. Fuel per Brake Horsepower

$$\text{lb. fuel/Hr/CBHP} = \frac{\text{lb.}}{\text{CBHP-Hr.}}$$

13. Indicated Mean Effective Pressure

$$\text{IHP} = \frac{\text{PLAN}}{33{,}000} \quad \text{(by definition)}$$

Therefore $P = \frac{\text{IHP}(33{,}000)}{\text{LAN}}$

where L = length of stroke

A = area of piston

N = number of power strokes per minute

$= \frac{\text{r.p.m.}}{2}$

In order to compensate for ambient conditions multiply

by the correction factor CF or rather than use IHP use CIHP.

Therefore $\quad IMEP = \dfrac{(CF)\,IHP(33{,}000)}{LAN} \quad$ (psi)

14. Fuel to Air Ratio

From the Ideal Gas Law, $PV = mR'T \quad V = \dfrac{mR'T}{P}$

$\rho = \dfrac{P}{mR'T}$ and R' for air $= 53.34$ ft-lbf/lbm. °R

Air density (ρ)

$$\rho = \text{Bar. Pres.} \cdot \frac{14.696}{29.92} \cdot \frac{144}{53.34 \cdot \text{Air Temp.}} \quad (\text{lb/ft}^3)$$

$$\text{Head of air } (h) = \frac{\text{ins. on manometer } (62.4)}{\text{Air Dens. } (12)} \quad (\text{ft. of air})$$

$$\text{Velocity} = C\sqrt{2gh} = 0.062\sqrt{64.4\,h} \quad (\text{Ft/min})$$

where C is the orifice coefficient.

$$\text{Flow} = \frac{\text{Vel (Area) 60 (Density)}}{144} \cdot \text{CF} \quad (\text{lb/hr})$$

$$\text{Fuel Air Ratio} = \frac{\text{lb fuel per hour}}{\text{lb air per hour}}$$

A sample calculation is shown in Appendix D.

A computer program, using Fortran IV language, was written by the author to do the above calculations. Besides doing the above calculations the program was designed to

calculate the fuel-air ratio from the exhaust gas analysis, as a check on the exhaust gas analysis. This program also rearranges all results in descending order of fuel-air ratio before printing them, and it also plots some of the results against fuel-air ratio. This program will also calculate the similar results, if the fuel is gasoline. The program is shown in Appendix E.

CHAPTER IV

RESULTS

4.1 EXPERIMENTAL RESULTS

A summary of the more pertinent results are tabulated in Table 4.1. A sample set of results, as calculated by the computer program is shown in Appendix F.

The results tabulated in Table 4.1 are shown plotted in Figs. 4.1 to 4.4 inclusive.

Fig. 4.1 shows the corrected (to Standard Atmospheric conditions) Indicated Mean Effective Pressure plotted against fuel-air ratio. As one would expect the m.e.p. decreases as the fuel-air ratio decreases. Increasing the compression ratio increases the m.e.p.

Fig. 4.2 is a plot of Indicated Thermal Efficiencies at various compression ratios plotted against fuel-air ratio. Increasing the compression ratio increases the thermal efficiency. As the fuel-air ratio decreases the thermal efficiency increases to a maximum value and then decreases.

TABLE 4.1

EXPERIMENTAL RESULTS

RUN	F/A Ratio (lb.fuel/lb.air)	CIHP (HP)	FU/CIHP (lb.fuel/HP)	FU/CBHP (lb.fuel/HP)	IMEP (psi)	I.Th.Eff (%)	B.Th.Eff (%)
Test 5	CR = 7.81						
1	0.0537	3.55	0.420	0.574	124.6	30.4	22.3
2	0.0448	3.34	0.371	0.515	119.2	34.4	24.8
3	0.0353	2.90	0.343	0.507	102.5	37.3	25.2
4	0.0342	2.70	0.359	0.553	94.9	35.6	23.1
5	0.0308	2.21	0.396	0.685	79.0	32.3	18.7
Test 5	CR = 9.77						
39	0.0577	3.65	0.459	0.635	128.7	27.9	20.1
40	0.0499	3.83	0.380	0.521	132.3	33.6	24.3
41	0.0416	3.60	0.336	0.466	127.8	38.1	27.4
42	0.0339	3.13	0.317	0.469	110.6	40.3	27.2
43	0.0267	2.30	0.344	0.620	80.4	37.1	20.6
Test 5	CR = 9.82						
48	0.0574	3.66	0.46	0.62	128.7	28.0	20.5
49	0.0501	3.80	0.38	0.51	133.2	33.5	24.8
50	0.0413	3.57	0.33	0.46	127.4	38.2	28.0
51	0.0320	2.96	0.32	0.47	104.8	40.4	27.1
52	0.0254	2.05	0.37	0.70	72.8	34.7	18.4

Test 6 CR = 9.5							
10	.0593	3.65	0.47	0.65	130.4	27.2	19.8
1	.0561	3.56	0.46	0.63	128.8	27.8	20.2
9	.0527	3.69	0.42	0.57	132.7	30.6	22.4
2	.0484	3.52	0.40	0.55	127.7	32.2	23.2
8	.0473	3.73	0.37	0.50	132.3	35.0	25.6
7	.0434	3.58	0.35	0.48	127.2	36.8	26.5
3	.0421	3.53	0.35	0.48	123.6	37.0	26.4
4	.0337	2.99	0.33	0.49	105.9	38.9	25.9
6	.0331	2.94	0.33	0.50	104.1	39.0	25.7
5	.0288	2.65	0.32	0.52	93.4	39.8	24.7
Test 7 CR = 9.00							
13	0.0423	3.57	0.35	0.49	125.0	36.7	26.3
14	0.0365	3.19	0.34	0.49	113.2	38.0	26.1
15	0.0318	2.83	0.33	0.51	101.2	38.4	25.0
Test 3 CR = 7.75 - No. 1 Gasoline							
4	0.0623	3.731	0.49	0.63	129.1	27.1	21.1
5	0.0540	3.707	0.42	0.54	130.4	31.7	24.7
6	0.0539	3.695	0.43	0.55	129.1	31.2	24.3
7	0.0450	3.371	0.40	0.53	119.5	33.4	25.4
7A	0.0619	3.653	0.50	0.65	127.0	26.7	20.5
8	0.0533	3.751	0.42	0.54	128.3	32.0	24.6
9	0.0491	3.677	0.39	0.51	127.3	33.9	26.1
11	0.0414	3.221	0.39	0.53	110.1	34.5	25.3
10	0.0388	3.073	0.38	0.52	106.9	35.0	25.4

Fig. 4.3 shows the effect of fuel-air ratio on Brake Thermal Efficiency. Increasing the compression ratio has a pronounced effect on increasing the brake thermal efficiency.

Fig. 4.4 shows "Comparative Fuel Consumption Loops" showing the relationship of Indicated Thermal Efficiency and Indicated Mean Effective Pressure and the effect of compression ratio.

4.2 THEORETICAL RESULTS

Fig. 4.5 shows a comparison of theoretical thermal efficiencies plotted against percent theoretical air for the results as obtained in this work with the earlier work of Goodenough and Baker [1], and results from Taylor [9] which he obtained by using the charts of Hottel, Williams, and Satterfield. The latter two sets of results are for gasoline as the fuel and are not primarily interested in very lean mixtures but range from lean to rich.

Figs. 4.6 and 4.7 show the effects of compression ratio and fuel-air ratio on the Theoretical Mean Effective Pressure and the Adiabatic Flame Temperature (T_3), respectively.

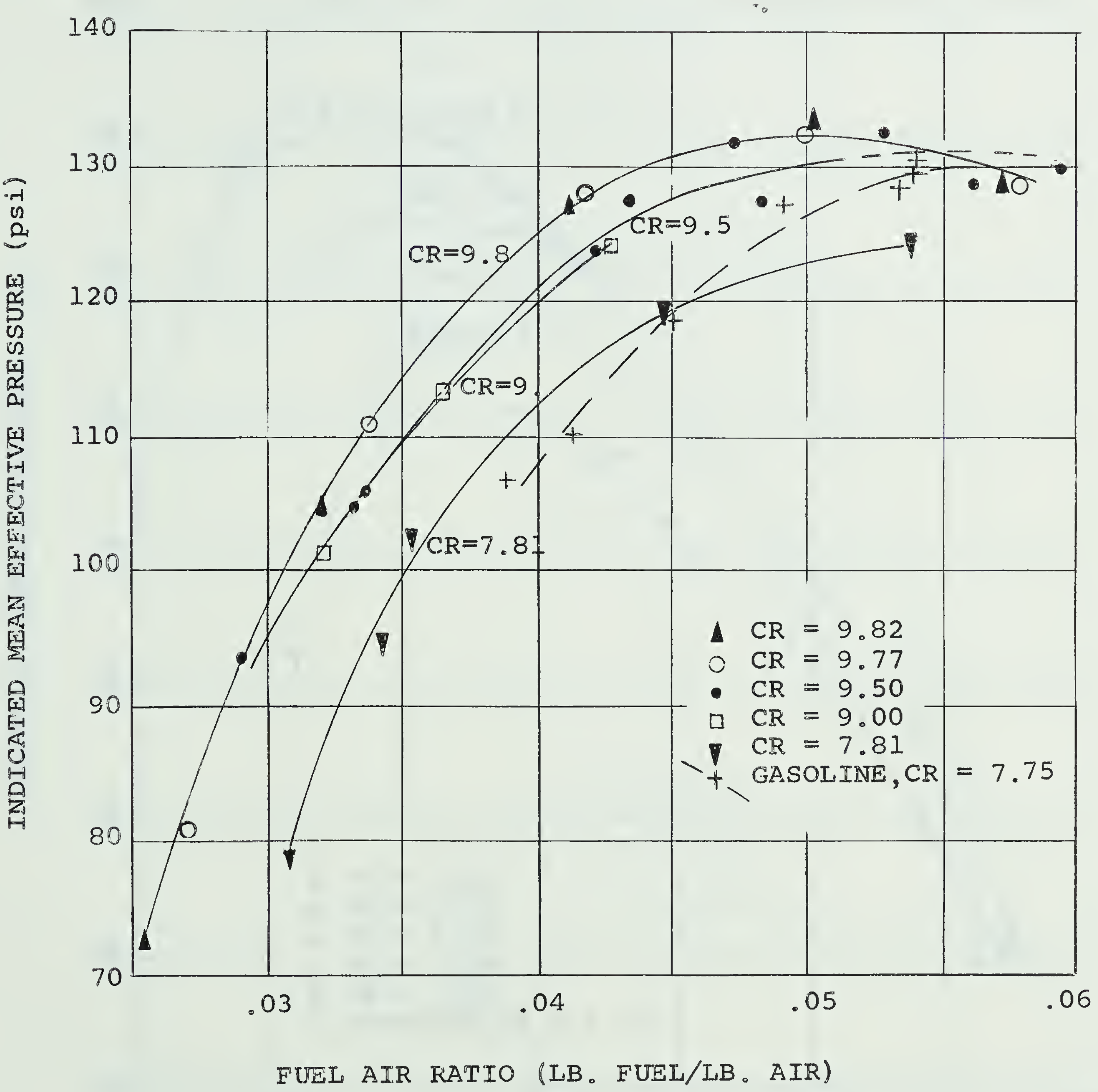


FIG. 4.1 INDICATED MEAN EFFECTIVE PRESSURE

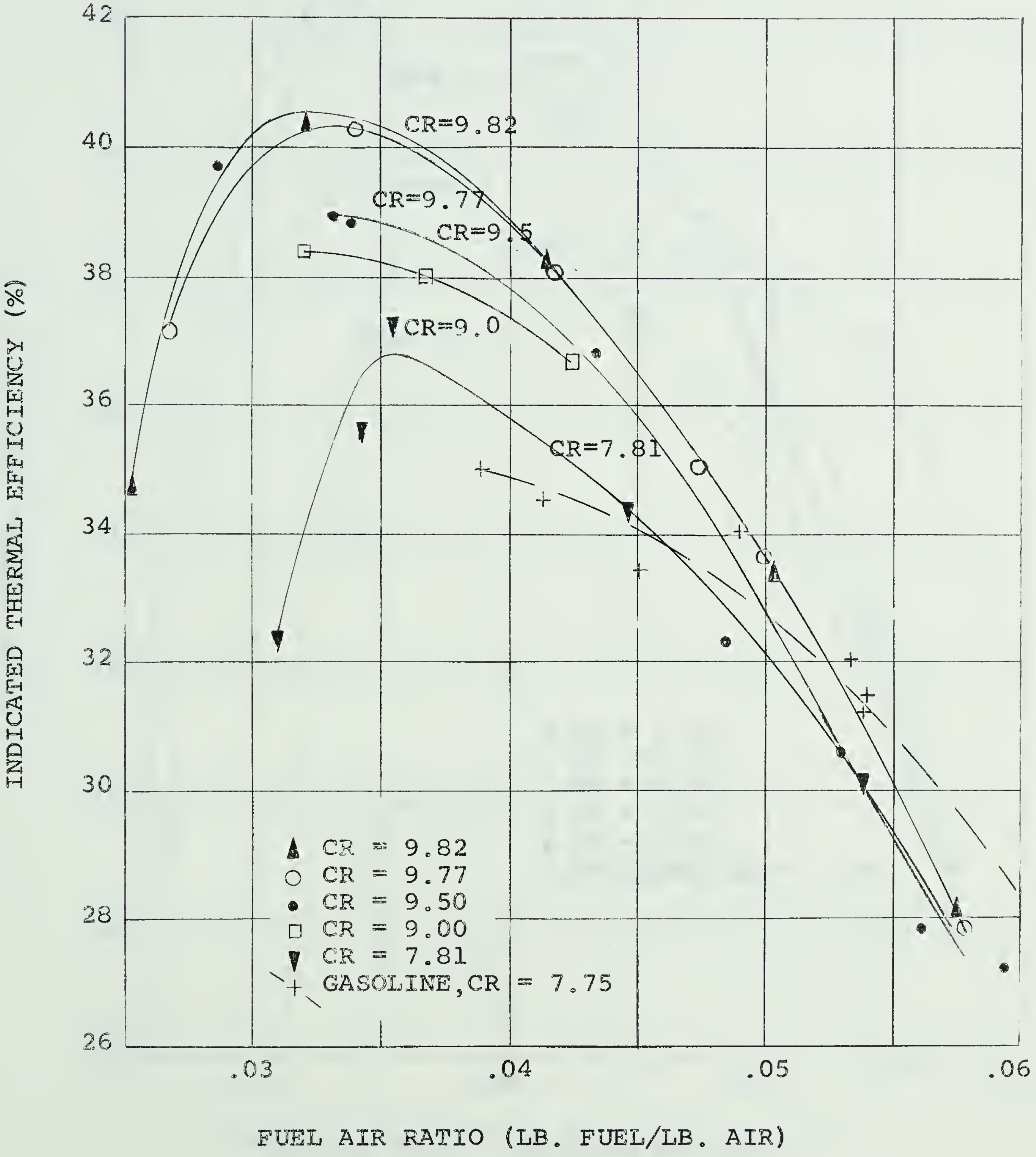


FIG. 4.2 INDICATED THERMAL EFFICIENCIES

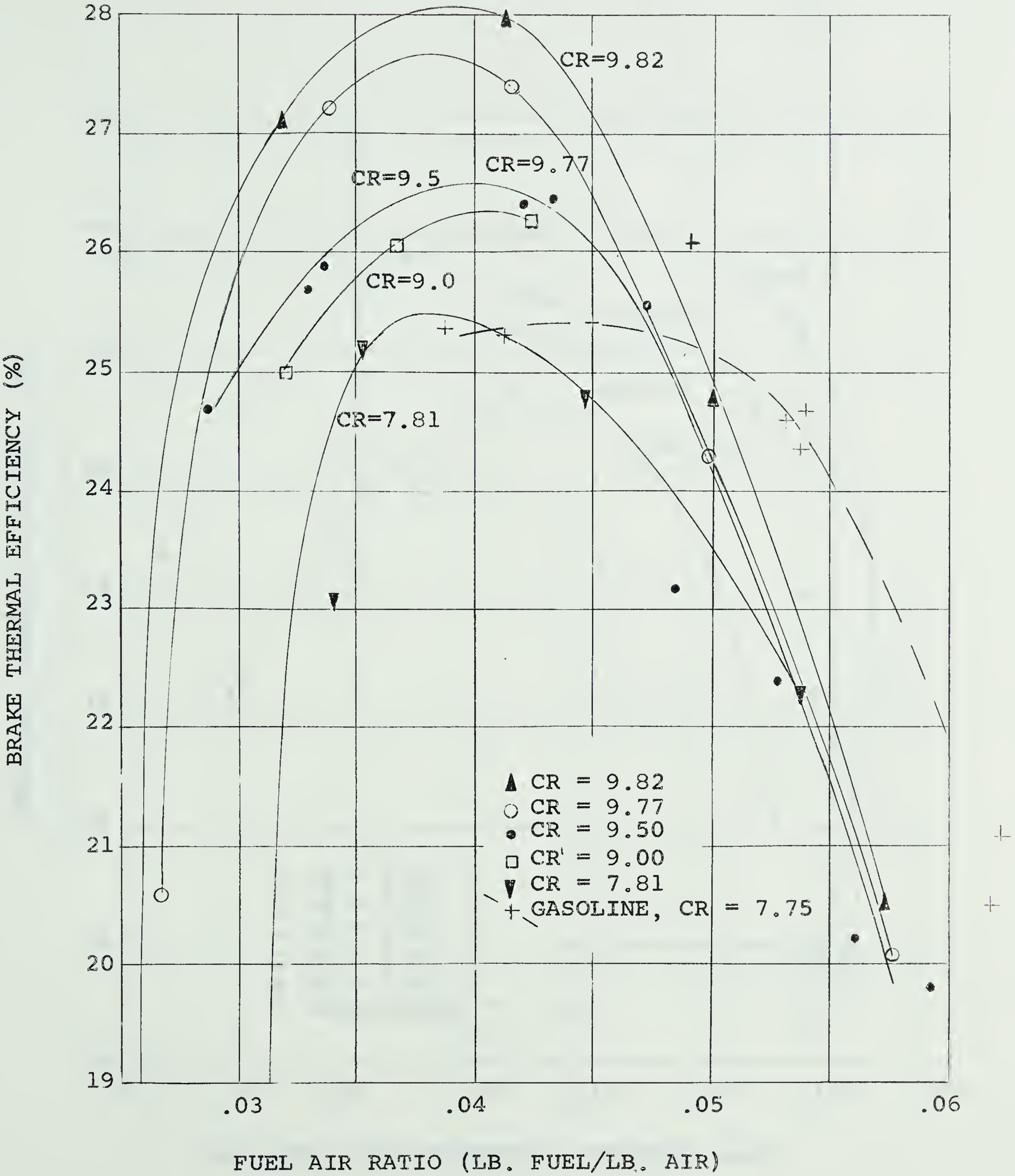


FIG. 4.3 BRAKE THERMAL EFFICIENCY

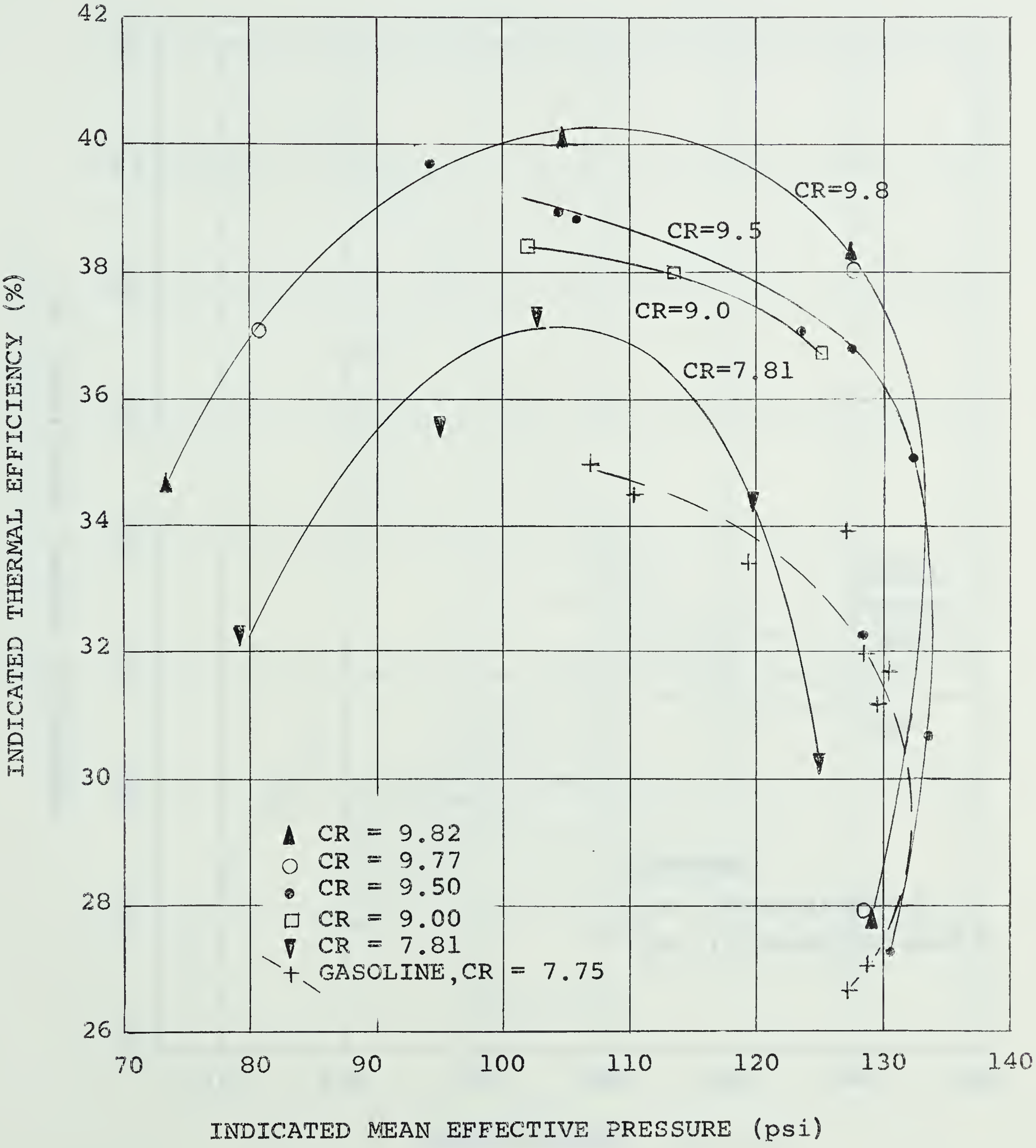


FIG. 4.4 "COMPARATIVE FUEL CONSUMPTION LOOPS"

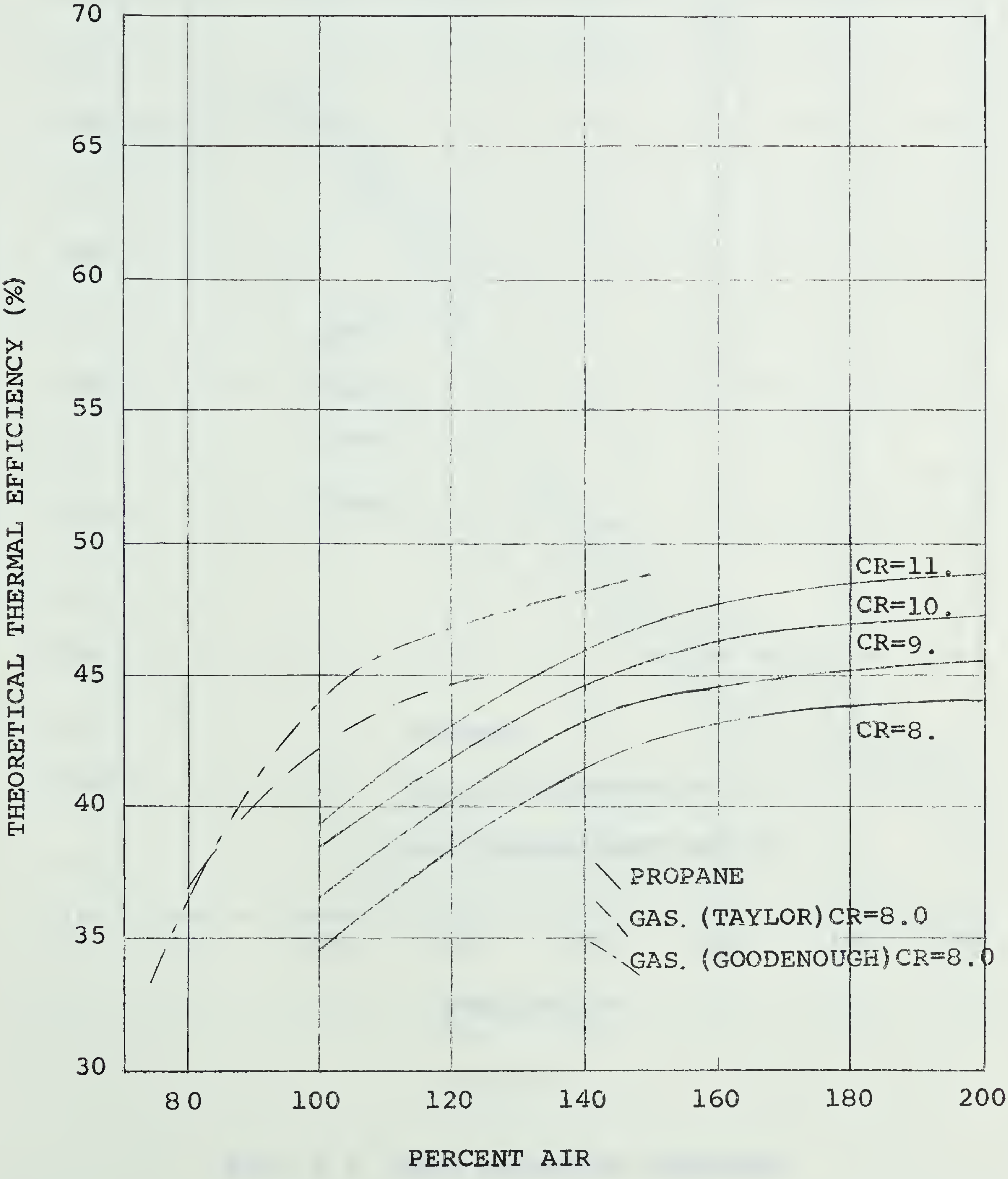


FIG. 4.5 THEORETICAL THERMAL EFFICIENCY

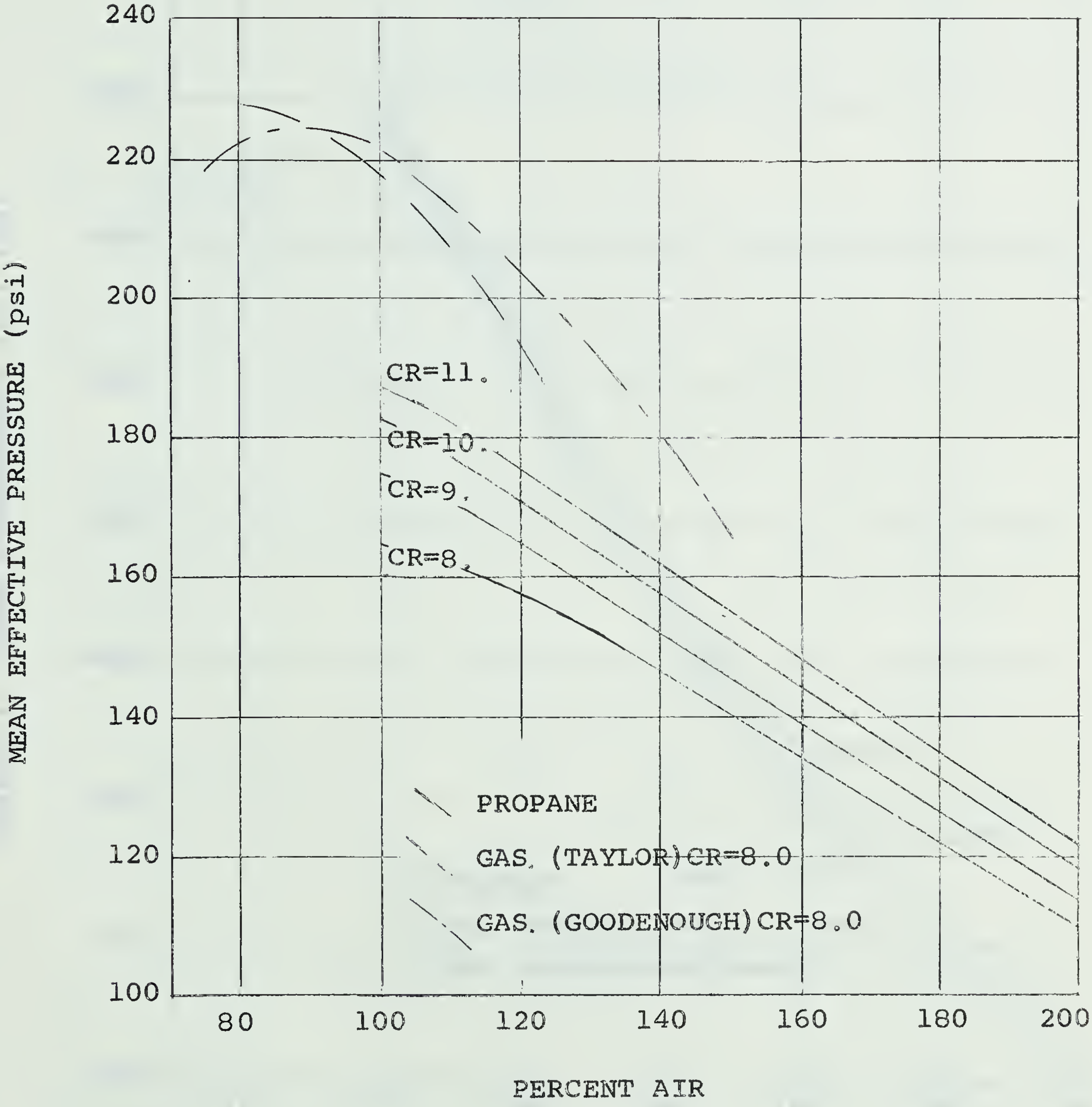


FIG. 4.6 MEAN EFFECTIVE PRESSURE

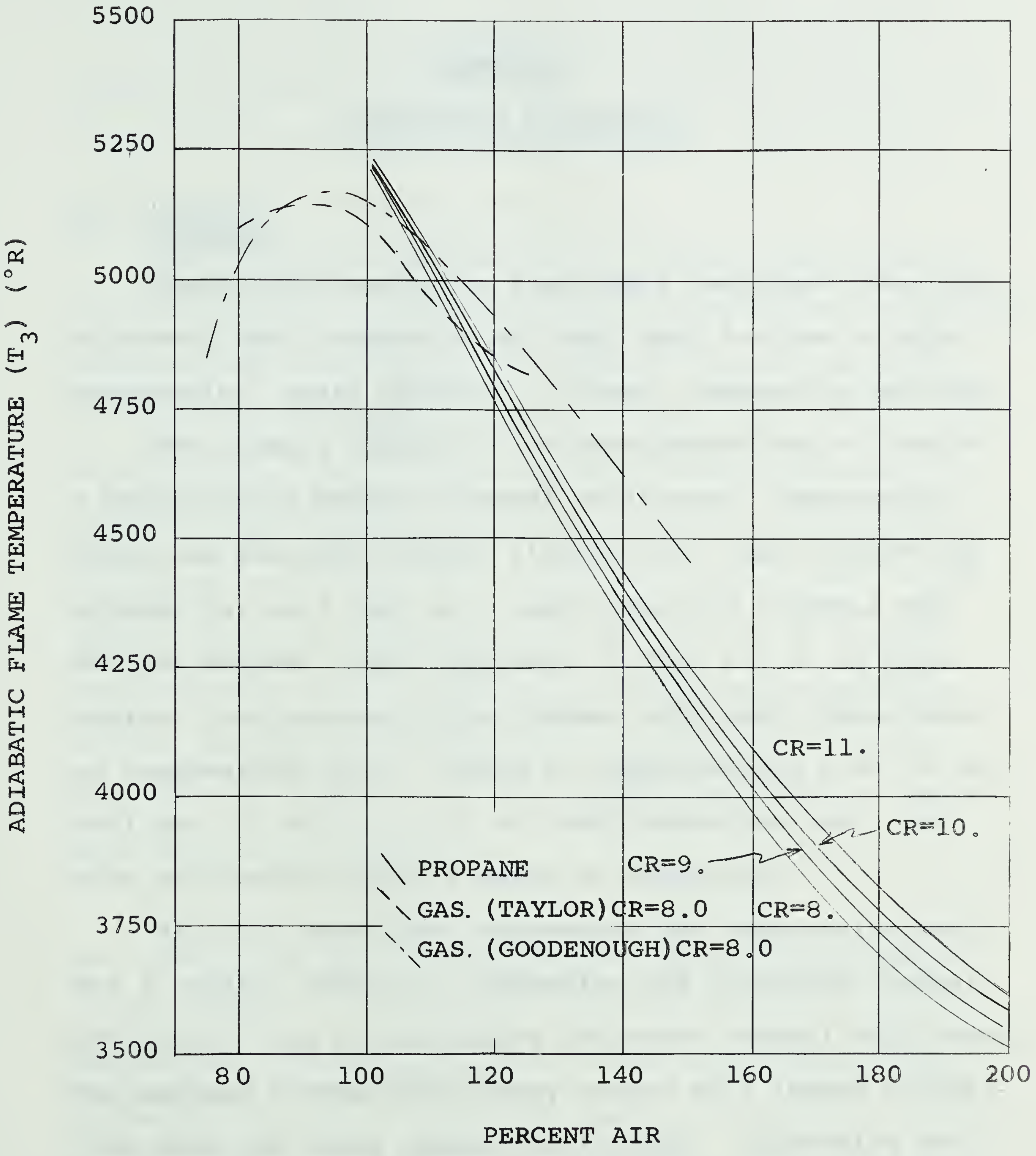


FIG. 4.7 ADIABATIC FLAME TEMPERATURE

CHAPTER V

DISCUSSION OF RESULTS

5.1 GENERAL

These experiments, as previously mentioned, show conclusively that propane is an ideal fuel for use in high compression, spark ignition, internal combustion engines.

The primary object of the experiments was to obtain a relationship between thermal efficiency, compression ratio and fuel-air mixture strength for lean mixtures of propane gas as a fuel in a spark ignition internal combustion engine. With reference to Fig. 4.3 it is quite obvious that maximum brake thermal efficiency regardless of compression ratio, occurs at approximately 0.04 lb. of fuel per lb. of air, i.e. at 160% theoretical air, for this particular engine running at 600 r.p.m.

Fig. 4.2 shows that increasing the compression ratio has a smaller effect on increasing the indicated thermal efficiency than on increasing the brake thermal efficiency. The maximum thermal efficiency occurs at a leaner mixture than does the brake thermal efficiency. Increasing the compression ratio causes the maximum indicated thermal efficiency to occur at a leaner mixture due to the increase in the fuel reaction rate as a result of the increased pressure.

Fig. 4.4 indicates as one would expect that the maximum thermal efficiency does not occur at maximum mean effective pressure but at approximately 100 to 110 psi regardless of the compression ratio.

With reference to Fig. 4.4 it may be concluded that for this engine running at 600 r.p.m. the maximum indicated mean effective pressure of the engine when the fuel is a lean mixture of propane at a compression of 9 or 10 is the same as the m.e.p. when the fuel is gasoline at a compression ratio of 7.75 (The highest CR at which the engine will operate without knock). However, the thermal efficiency of the engine when the fuel is propane is greater than when the fuel is gasoline at the lower compression ratio. Lowering the compression ratio results in a reduction in both the thermal efficiency and the indicated mean effective pressure.

5.2 COMPARISON - EXPERIMENTAL AND THEORETICAL RESULTS

Although the air standard Otto cycle indicates that the thermal efficiency for air increases to 100 percent (equation 2.3) this is not the case with fuel-air mixtures even though the mixture may be made leaner, i.e. approaching 100% air. The efficiency reaches a maximum value and then decreases, prior to the leanest mixture on which the engine will continue to run smoothly. This may be

attributable to the fact that the engine must rely on the fuel, only, for its heat, which is not the case when using the ideal cycle for air. An optimum fuel-air ratio is reached beyond which, due to the great excess of air, the fuel does not ignite.

Although the thermal efficiencies and brake mean effective pressures obtained experimentally are lower than the theoretical results, due to losses previously mentioned in Chapter II, when the curves are compared they both have the same general trends and experimental results are approximately 70% of the theoretical results.

5.3 EXPERIMENTAL ERROR

Although as many variables as possible were controlled and a correction factor applied to relate all calculations affected by ambient conditions to a standard base, variations in ambient conditions did affect results. As an example, the rate of heat transfer from the engine and from the room into the intake manifold vary as the room temperature changes and these variations, which could not be determined, did have an effect on the operation of the engine.

Speed fluctuated during tests, even though the settings were unaltered. These flucuations, at very lean mixtures were in the order of 5% and although they would

have a minimal effect on the averaged rates of fuel and air consumption they would have an effect on the torque. In an effort to compensate for this, all readings were taken in the same order for each test. It may also be due to these flucuations that some of the exhaust gas analyses were incorrect.

5.4 MISCELLANEOUS OBSERVATIONS

The engine operates smoothly on fuel-air ratios down to approximately 0.028 lb. propane/lb. air (230% air) at which point the engine begins to misfire due to incomplete combustion of the fuel.

The mean temperature of the combustion chamber is less than 1000 °F in the range tested, ranging from 900° at the higher fuel-air ratio down to approximately 500° at the very lean mixtures. The mean temperature is lower when using propane than when using gasoline as the fuel.

The mild steel exhaust valve functioned well during the 23 hrs. it was installed. There was no loss of compression due to corrosion and observation indicates no apparent corrosion of the valve. An attempt was made to measure the exhaust valve temperature by means of a thermocouple mounted flush in the face of the valve and the wires extending through a hole drilled axially along the valve. In order to avoid modification of the rocker

arm mechanism a radial hole was drilled at the top of the valve stem just below the rocker arm to bring out the thermocouple wires. This procedure did not work due to the fact the valve rotates and the thermocouple wire insulation frayed and shorted the wires.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

This thesis has described a theoretical and experimental investigation of the burning of lean mixtures of propane gas in a spark ignition internal combustion engine. It has been shown that lean mixtures of propane are satisfactory for the operation of spark ignition internal combustion engines.

Although the theoretical analysis indicates higher thermal efficiencies and higher mean effective pressures than obtained experimentally, both sets of results, in general, have the same trends. The reason that the results obtained from the theoretical analysis are higher than the results obtained experimentally may be attributed to the fact that the theoretical analysis is for an ideal fuel-air cycle i.e. the processes are assumed to be adiabatic with isentropic compression and expansion and the effects of pressure losses during the induction and exhaust processes are ignored. The mean effective pressures obtained experimentally are approximately 70% of the values obtained by the theoretical analysis. The theoretical thermal efficiency shows a continuous increase, reaching a maximum of 48.5% at a CR = 11 and 200% air (The limit of this calculation). The rate of increase decreases as the mixture becomes leaner. The indicated thermal

efficiency, obtained experimentally, initially shows an increase as the air is increased but it reaches a maximum value of 40.5% at CR = 9.8 and then decreases quite rapidly. The fact that the thermal efficiency reaches a maximum and then decreases may be attributed to the effect of heat transfer from the combustion chamber. As the fuel air mixture becomes leaner a fuel-air ratio is reached where the amount of heat transfer becomes greater than the amount of heat available to do work on the piston thus causing a decrease in the thermal efficiency. Increasing the compression ratio causes an increase in both the thermal efficiency and the mean effective pressure in both the theoretical analysis and experimental analysis. Increasing the compression ratio also causes the maximum thermal efficiency, as obtained experimentally, to occur at a leaner mixture, due to the combustion process approaching a constant volume burning, in a shorter time interval, thus reducing the amount of heat transfer.

Maximum fuel economy, as indicated by the brake thermal efficiency, is obtained when the fuel-air ratio is at 0.04 lb. of propane per lb. of air (160% of theoretical air) at an engine speed of 600 r.p.m. The compression ratio has a negligible effect on the maximum brake thermal efficiency and maximum fuel economy.

Lean mixtures of propane and gasoline, both at the

highest compression ratio without knock, result in approximately the same maximum mean effective pressure, 132 psi. However, since propane is knock free at higher CR's the thermal efficiency of propane at a higher CR is greater than gasoline at the highest CR it may be used (7.75).

Lean mixtures of propane result in a lower engine operating temperature than when the engine is burning gasoline.

There is no apparent oxidation of the exhaust valve when the engine is operating on lean mixtures of propane.

6.2 APPLICATIONS

When designing an engine, or increasing the CR of any existing engine, a considerable saving in operating costs may be realized by using lean fuel-air mixtures of propane as the fuel which also results in fewer oil changes and less engine wear than could be obtained if using gasoline as the fuel, in a lower CR engine. If the engine is operated at maximum thermal efficiency for a fixed speed, less fuel will be required thus resulting in a further saving. At times when greater power is required i.e. for accelerating there will be a momentary reduction in thermal efficiency but the fuel-air ratio may then be re-adjusted to again give maximum thermal efficiency.

6.3 RECOMMENDATIONS

Further work should be done in this area to determine the effect of engine speed on the maximum thermal efficiency.

Comparative tests at part throttle should also be investigated.

Since inlet mixture temperature has an effect on thermal efficiency a worthwhile increase in thermal efficiency may be realized by using the latent heat of the liquified propane to cool the inlet fuel-air mixture.

Since engines using lean mixtures are difficult to start in cold weather an investigation should also be conducted to determine the relationship between the fuel-air ratio and minimum fuel-air temperature for starting, and for very cold weather operation.

In order to avoid misfiring at very lean mixtures, and to see if the maximum thermal efficiency may be further increased at leaner mixtures, the effect of a stratified charge, i.e. rich at the spark plug and lean throughout the combustion chamber, should be further investigated using propane as the fuel.

The theoretical analysis should be further improved to take into consideration the effects of heat transfer between the cylinder wall and charge during the entire cycle rather than assume an adiabatic process. Consideration should also be given to the effect of the pressure losses involved during the induction and exhaust processes.

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APPENDIX A

SAMPLE THEORETICAL CALCULATION

Based on the equations of Chapter II and assuming 100% theoretical air, a compression ratio of 9.0 and the fuel and air entering at 536.6 °R.

Note: U's and Φ's are taken from table [11] if listed in the table.

For the initial calculation assume the residual gas fraction = .027 and T_5 = 2300 °R.

from equation 2.2-2 -

$$C_3H_8 + 5O_2 + 18.8N_2 + .027(3CO_2 + 4H_2 + 18.8N_2) \longrightarrow$$

$$3(1.027)CO_2 + 4(1.027)H_2O + 18.8(1.027)N_2$$

$$\begin{aligned} \text{Moles of charge} &= 1 + 5 + 18.8 + 0.27(3 + 4 + 18.8) \\ &= 24.8 + .027(25.8) \\ &= 24.8 + .697 = 25.497 \text{ moles} \end{aligned}$$

$$\begin{aligned} \text{Moles of products} &= (3 + 4 + 18.8)1.027 \\ &= (25.8)1.027 = 26.497 \text{ moles} \end{aligned}$$

from equation 2.2-3 -

$$U_1 = H_{fuel} + H_{O_2} + H_{N_2} + U_{res.gas} - M(1.986)T_1\left(1 - \frac{1}{CR}\right)$$

$$= 5(83) + 18.8(81) + 23.8(1066) + 180 + 1066 + U_{res.gas}$$

$$- M(1.986)T_1 \left(\frac{8}{9}\right)$$

$$= 28{,}551 + U_{res} - M(1.986)T_1 \left(\frac{8}{9}\right)$$

Energy of residual gas -

$$U_{CO_2} = 3(.027)\ 17{,}680 = 1430$$

$$U_{H_2O} = 4(.027)\ 12{,}835 = 1388$$

$$U_{N_2} = 18.8(.027)\ 9{,}817 = \underline{4980}$$

$$U_{res} = \underline{7798 \text{ BTU}}$$

Try $T_1 = 600^\circ$

$$U_1 = 28{,}551 + 7798 - 25.497(1.986)\ \frac{8}{9}(600)$$

$$= 36{,}349 - 45.0(600)$$

$$= 36{,}349 - 27{,}000 = \underline{9{,}349 \text{ BTU}}$$

Considering mixture at 600

$$U_{C_3H_8} = .272(600 - 520) + .0160(600^2 - 520^2) - \frac{543}{3 \times 10^8}$$

$$(600^2 - 520^2)$$

$$= .272(80) + .0160(1120)80 - \frac{543}{3 \times 10^2}\ (216 - 141)$$

$$= 21.8 + 143.3 - 134.0$$

$$= 1412.8 \text{ BTU}$$

$$U_{O_2} = 5(402) = 2010 = 2010$$

$$U_{N_2} = 18.8(1.027)395 = (19.3)395 = 7430$$

$$U_{CO_2} = 3(.027)570 = (.081)570 = 46$$

$$U_{H_2O} = 4(.027)490 = (.108)490 = \underline{53}$$

$$\sum U_1 = \underline{10,952} \text{ BTU}$$

<u>Try $T_1 = 580^\circ$</u>

$$U_1 = 36,349 - 45.0(580) = 36,349 - 26,100 = 10,249 \text{ BTU}$$

<u>Consider mixture at 580°</u>

$$U_{C_3H_8} = .272(60) + .0160(1100)60 - \frac{543}{3 \times 10^2}(194 - 141)$$

$$= 16.3 + 105.9 - 97.7 = 977.6$$

$$U_{O_2} = 5(301) = 1505$$

$$U_{N_2} = 19.3(295) = 5690$$

$$U_{CO_2} = .081(424) = 34.4$$

$$U_{H_2O} = .108(490) = \underline{53}$$

$$\sum U = \underline{8260.0} \text{ BTU}$$

$\therefore$ T_1 is between 580 and 600°R. Do a linear interpolation to get T_1.

$$\frac{DT}{10{,}249 - 8260} = \frac{20 - DT}{10{,}952 - 9349}$$

$$DT = \frac{20(1989)}{1989 + 1603} = \frac{20(1989)}{3592} = 11.1$$

$$\therefore \quad T_1 = 580 + 11 = \underline{\underline{591\,^\circ R}}$$

<u>Adiabatic compression from T_1 to T_2</u>

$$\phi_{C_3H_8} = .272 \ln \frac{591}{520} + .0320(591 - 520) - \frac{543}{2 \times 10^8}(591^2 - 520^2)$$

$$= .272 \ln 1.138 + .0320(71) - \frac{543}{2 \times 10^8}(1111)71$$

$$= .0351 + 2.27 - .214 = 2.091$$

$$\phi_{O_2} = 5\left(.56 + \frac{11}{21}(.75 - 56)\right) = 5(.56 + .10) = 5(.66) = 3.30$$

$$\phi_{N_2} = 19.3(.54 + \frac{11}{20}(.72 - .54) = 19.3(.54 + .10)$$

$$= 19.3(.64) = 12.33$$

$$\phi_{CO_2} = .081\left(.77 + \frac{11}{20}(1.02 - .77)\right) = .081(.77 + .138)$$

$$= .081(.908) = .07$$

$$\phi_{H_2O} = .108\left(.71 + \frac{11}{20}(.94 - .71)\right) = .108(.71 + .126)$$

$$= .108(.836) = .09$$

$$\sum \phi_{591} = \underline{17.88}$$

Try $T_2 = 1200$

$$\phi_{C_3H_8} = .272 \ln \frac{1200}{520} + .0320(1200 - 520) - \frac{543}{3 \times 10^8}(1200^2 - 520^2)$$

$$= .272 \ln 2{\cdot}31 + .0320(680) - \frac{543}{3 \times 10^8}(1720)680$$

$$= .228 + 21.8 - 3.18$$

$$= 18.85$$

$$\phi_{O_2} = 5(4.50) = 22.50$$

$$\phi_{N_2} = 19.3(4.25) = 83.00$$

$$\phi_{CO_2} = .081(6.91) \quad .56$$

$$\phi_{H_2O} = .108(5.31) \quad \underline{.57}$$

$$\sum \phi_{1200} = \underline{125.48}$$

$$\Delta s = \sum \phi_{1200} - \sum \phi_{591} - 1.986(M) \ln CR$$

$$= 125.48 - 17.88 - 1.986(25.497) \ln 9$$

$$= 125.48 - 17.88 - 111.2$$

$$= 125.48 - 129.08 = \underline{-3.60} \text{ BTU}$$

$\therefore$ T_2 assumed too low

Try $T_2 = 1300$

$$\phi_{C_3H_8} = .272 \ln \frac{1300}{520} + .0320(1300 - 520) - \frac{543}{2 \times 10^8}(1300^2 - 520^2)$$

$$= .272 \ln 2.5 + .0320(780) - \frac{543}{2 \times 10^8}(1820)780$$

$$= .249 + 24.9 - 3.86 = 21.29$$

$$\phi_{O_2} = 5(4.98) = 24.9$$

$$\phi_{N_2} = 19.3(4.68) = 90.2$$

$$\phi_{CO_2} = .081(7.69) = .62$$

$$\phi_{H_2O} = .108(5.85) = \underline{.63}$$

$$\sum \phi_{1300} = \underline{137.64}$$

$$\Delta s = 137.64 - 17.88 - 111.2$$

$$= 137.64 - 129.08 = \underline{8.56} \text{ BTU}$$

Linear interpolation to get T_2

$$DT = \frac{100(3.60)}{3.60 + 8.56} = \frac{360}{12.16} = 29.6$$

$$\therefore \quad T_2 = 1200 + 30 = \underline{\underline{1230^\circ R}}$$

<u>Determine the energy of mixture at 1230°</u>

$$U_{C_3H_8} = .272T_2 + .016T^2 - \frac{543}{3 \times 10^8} T_3$$

$$= .272(1230 - 520) + .016(1230^2 - 520^2) - \frac{543}{3 \times 10^8}$$

$$(1230^3 - 520^3)$$

$$= .272(710) + .016(1750)710 - \frac{543}{3 \times 10^2}(1860 - 163)$$

$$= .272(710) + .016(1750)710 - \frac{543}{300}(1697)$$

$$= 193 + 19{,}870 - 3077 = 16{,}986 \text{ BTU}$$

$$U_{O_2} = 5\left(3675 + .3(4263 - 3675)\right) = 5(3851) = 19{,}240$$

$$U_{N_2} = 19.3\left(3461 + .3(3996 - 3461)\right) = 19.3(3622) = 69{,}900$$

$$U_{CO_2} = .081\left(5736 + .3(6721 - 5736)\right) = .081(6032) = 488$$

$$U_{H_2O} = .108\left(4339 + .3(5030 - 4339)\right) = .108(4546) = 491$$

$$U_2 = \underline{107{,}105 \text{BTU}}$$

$$CE_{C_3H_8} = 878{,}822 \text{ B/mole}$$

$\therefore$ Total energy $= 878{,}822 + 107{,}105 = \underline{985{,}927}$ BTU

Substitute into equation 2.2-11 and add like terms.

<u>Assume $T_3 = 5200\,^\circ R$</u>

Product	Numerical Terms	x terms	y terms
$3.081(x)CO$		90,200	
$3.081(1-x)CO_2$	166,000	-166,000	
$4.108(y)H_2$			111,200
$4.108(1-y)H_2O$	172,500		-172,500
$\left[\frac{3}{2}(x) + \frac{4}{2}(y)\right](1.027)O_2$		47,900	63,900
$19.3N_2$	559,000		
$\sum$	897,500	-27,900(x)	2,600(y)

$$CE_{CO} = 3(1.027)(x)\ 121{,}181 = 373{,}000\ (x)$$

$$CE_{H_2} = 4(1.027)(y)\ 103{,}486 = 424{,}500\ (y)$$

Energy balance gives: -

$$985{,}927 = 897{,}500 - 27{,}900(x) + 2{,}600(y) + 373{,}000(x) + 424{,}500(y)$$

$$\therefore 88{,}427 = 345{,}100(x) + 427{,}100(y)$$

$$\therefore \quad y = \frac{88{,}427 - 345{,}100(x)}{427{,}100}$$

$$= 0.2065 - 0.808x$$

From the tables [12] $\log K_{WG} = 0.829$

$$\therefore \quad K_{WG} = 6.75$$

Substitute into equation 2.2-13

$$\therefore \quad y = \frac{x}{6.75 - 5.75x}$$

Equating y's

$$y = 0.2065 - 0.808x = \frac{x}{6.75 - 5.75x}$$

$$\therefore (0.2065 - 0.808x)(6.75 - 5.75x) = x$$

$$1.393 - 5.45x - 1.189x + 4.65x^2 = x$$

$$\therefore \quad 4.65x^2 - 7.639x + 1.393 = 0$$

$$x = \frac{7.639 - \sqrt{(7.639)^2 - 4(4.65)1.393}}{2(4.65)}$$

$$= \frac{7.639 - \sqrt{58.3 - 25.9}}{2(4.65)}$$

$$= \frac{7.639 - 5.69}{2(4.65)}$$

$$= \frac{1.949}{2(4.65)} = \underline{0.2097}$$

$$\therefore \quad y = 0.2065 - 0.808(0.2097)$$

$$= 0.2065 - 0.1692 = \underline{0.0373}$$

Obtain P_2 from $P_2 = \dfrac{CR(T_2)(P_1)}{T_1}$

$$P_2 = \frac{9(1230)(1)}{591} = \underline{\underline{18.73}} \text{ atm.}$$

Obtain K_{CO_2}, using equation 2.2-8

$$K_{CO_2} = \left(\frac{x}{1-x}\right)^2 \left[\frac{3}{2}(1+f)x + \frac{4}{2}(1+f)y\right] \frac{P_2 \cdot T_3}{M_2 \cdot T_2}$$

$$= \left(\frac{0.2097}{1 - 0.2097}\right)^2 \left[\frac{3.081}{2}(.2097) + \frac{4.108}{2}(.0373)\right]$$

$$\frac{18.73(5200)}{25.497(1230)}$$

$$= \left(\frac{0.2097}{0.7903}\right)^2 \left[0.322 + 0.0765\right] \frac{18.73(5200)}{25.497(1230)}$$

$$= (.265)^2 \, (.3958) \, \frac{18.73(5200)}{25.497(1230)} = \underline{.0861}$$

From the Tables [12] $\log K_{CO_2} = -1.32$

$$K_{CO_2} = \underline{0.048}$$

$\therefore$ T_3 assumed too low

<u>Try T_3 = 5400</u>

Product	Numerical Terms	x terms	y terms
$3(1.027)(x)CO$		94,300	
$3(1.027)(1-x)CO_2$	174,000	-174,000	
$4(1.027)(y)H_2$			117,000
$4(1.027)(1-y)H_2O$	182,000		-182,000
$\left[\frac{3}{2}(x) + \frac{4}{2}(y)\right](1.027)O_2$		50,200	66,900
$19.3\ N_2$	585,000		
$\sum$	941,000	-29,500(x)	1,900(y)

Energy balance gives:-

$$985{,}927 = 941{,}000 - 29{,}500(x) + 1{,}900(y) + 373{,}000(x) + 424{,}500(y)$$

$$\therefore\ 44{,}927 = 343{,}500(x) + 426{,}400(y)$$

$$\therefore\ y = \frac{44{,}927 - 343{,}500(x)}{426{,}400}$$

$$= 0.1052 - 0.805(x)$$

From Tables [12] $\log K_{WG} = 0.840$

$$\therefore\ K_{WG} = 7.06$$

$$\therefore \quad y = \frac{x}{7.06 - 6.06(x)}$$

Equating y's

$$y = 0.1052 - 0.805x = \frac{x}{7.06 - 6.06x}$$

$$\therefore \quad (0.1052 - 0.805x)(7.06 - 6.06x) = x$$

$$0.743 - 5.68x - 0.638x + 4.88x^2 = x$$

$$\therefore \quad 4.88x^2 - 7.318x + 0.743 = 0$$

$$x = \frac{7.318 - \sqrt{(7.318)^2 - 4(4.88)0.743}}{2(4.88)}$$

$$= \frac{7.318 - \sqrt{53.5 - 14.5}}{2(4.88)}$$

$$= \frac{7.318 - 6.24}{2(4.88)} = \frac{1.078}{2(4.88)} = \underline{0.1102}$$

$$y = 0.1052 - 0.805(0.1102)$$

$$= 0.1052 - 0.0887 = \underline{0.0165}$$

$$\therefore K_{CO_2} = \left(\frac{0.1102}{1 - 0.1102}\right)^2 \left[\frac{3.981}{2}(.1102) + \frac{4.108}{2}(.0165)\right]$$

$$\frac{18.73(5400)}{25.497(1230)}$$

$$= \left(\frac{0.1102}{0.8898}\right)^2 \left[0.1699 + 0.0338\right] \frac{18.73(5400)}{25.497(1230)}$$

$$= (0.125)^2 \left[0.2037\right] \frac{18.73(5400)}{25.497(1230)} = \underline{0.01027}$$

From Tables [12] $\log K_{CO_2} = -0.94$

$$\therefore \quad K_{CO_2} = \underline{0.115}$$

$$\therefore \quad T_3 = 5400\,^{\circ}R \text{ is too high}$$

Do a linear interpolation to obtain T_3, x_3 and y_3.

$$\frac{DT}{0.0861 - 0.048} = \frac{200 - DT}{0.115 - 0.01027}$$

$$\therefore \quad DT = \frac{0.0381(200)}{0.0381 + 0.10473} = \frac{0.0381(200)}{0.14283}$$

$$= 53.4$$

$$\therefore \quad T_3 = 5200 + 53.4 = \underline{\underline{5253.4\,^{\circ}R}}$$

$$x_3 = 0.2097 - \frac{53.4}{200}(0.2097 - 0.1102) = .2097 - .0266$$

$$= \underline{\underline{0.1831}}$$

$$y_3 = 0.0373 - \frac{53.4}{200}(0.0373 - 0.0165) = .0373 - .0055$$

$$= \underline{\underline{0.0318}}$$

<u>Entropy at T_3</u>

Using equation 2.2-14

$$s_3 = \sum \phi - \sum MR \ln pp + \frac{M_{CO}\, CE_{CO}}{T_3} + \frac{M_{H_2}\, CE_{H_2}}{T_3}$$

$$\phi_{CO_2} = 3.081(1 - .1831)\left[27.98 + \frac{253}{500}(29.51 - 27.98)\right]$$

$$= 3.081(0.8169)\left[27.98 + 0.774\right]$$

[illegible]

[illegible]

[illegible]

[illegible]

$$[illegible]$$

[illegible]

[illegible]

$$[illegible]$$

$$[illegible]$$

[illegible]

[illegible]

$$[illegible]$$

[illegible]

$$= 3.081(0.8169)(28.754) = 72.2$$

$$\phi_{CO} = 3.081(0.1831)\left[17.72 + \frac{253}{500}(18.57 - 17.72)\right]$$

$$= 3.081(0.1831)\left[17.72 + 0.43\right]$$

$$= 3.081(0.1831)(18.15) = 10.22$$

$$\phi_{H_2O} = 4.108(1 - .0318)\left[22.42 + \frac{253}{500}(23.65 - 22.42)\right]$$

$$= 4.108(1 - .0318)(22.42 + 0.622)$$

$$= 4.108(0.9682)(23.042) = 91.6$$

$$\phi_{H_2} = 4.108(0.0318)\left[16.81 + \frac{253}{500}(17.65 - 16.81)\right]$$

$$= 4.108(0.0318)(16.81 + 0.424)$$

$$= 4.108(0.0318)(17.234) = 2.25$$

$$\phi_{O_2} = \left[\frac{3.081}{2}(0.1831) + \frac{4.108}{2}(0.0318)\right]\left[18.49 + \frac{253}{500}(19.38 - 18.49)\right]$$

$$= (0.282 + 0.0645)(18.49 + 0.45)$$

$$= 0.3465(18.94) = 6.57$$

$$\phi_{N_2} = 19.3\left[17.54 + \frac{253}{500}(18.38 - 17.54)\right]$$

$$= 19.3(17.54 - 0.424) = 19.3(17.964) = 346.8$$

$$\sum \phi = \underline{529.64} \text{ BTU}$$

$$P_3 = \frac{M_3}{M_2} \cdot \frac{T_3}{T_2} \cdot P_2$$

$$M_3 = 3.081 + 4.108 + 19.3 + 0.3465 = \underline{\underline{26.8355}} \text{ moles}$$

$$\therefore \quad P_3 = \frac{26.8355}{25.497} \cdot \frac{5253}{1230} \cdot 18.73 = \underline{\underline{84.3}} \text{ atm.}$$

Constituent	pp	ln pp	1.986(M)ln pp
$3.081(0.8169)CO_2$	7.90	2.065	10.31
$3.081(0.1831)CO$	1.77	0.572	0.64
$4.108(0.9682)H_2O$	12.46	2.52	19.83
$4.108(0.0318)H_2$	0.41	-0.891	-0.231
$0.3465O_2$	1.09	0.0862	0.059
$19.30N_2$	60.60	4.11	157.4
		$\sum$	188.01

$$\therefore \quad s_3 = 529.64 - 188.01 + \frac{3.081(.1831)121{,}181}{5253}$$

$$+ \frac{4.108(.0318)103{,}486}{5253}$$

$$= 529.64 - 188.01 + 13.00 + 2.57$$

$$= \underline{\underline{357.20}} \text{ BTU}$$

<u>To find T_4</u>

<u>Assume $T_4 = 3300\,^\circ R$</u>

from Tables, [12], $\log K_{CO_2} = -7.08$ and $\log K_{WG} = 0.593$

$$\therefore \; K_{CO_2} = 8.32 \times 10^{-8} \qquad K_{WG} = 3.92$$

Try x = 0.006

Substituting in equation 2.2-15

$$K_{CO_2} = \left(\frac{0.006}{0.994}\right)^2 \left[\frac{3.081(.006)}{2} + \frac{4.108(.006)}{2(3.92 - 2.92(.006))}\right] \frac{3300}{25.497(591)}$$

$$= 4.01 \times 10^{-5} \left[0.00924 + \frac{4.108(0.003)}{3.92 - 0.0175}\right] \frac{3300}{25.497(591)}$$

$$= 4.01 \times 10^{-5} \left[0.00924 + 0.00315\right] 0.219$$

$$= 4.01 \times 10^{-5} \left[0.01239\right] 0.219$$

$$= \underline{1.09 \times 10^{-7}}$$

Try x = 0.0057

$$K_{CO_2} = \left(\frac{0.0057}{0.9943}\right)^2 \left[\frac{3.081(.0057)}{2} + \frac{4.108(.0057)}{2(3.92 - 2.92(.0057))}\right] 0.219$$

$$= 3.28 \times 10^{-5} \left[0.00876 + \frac{4.108(.0057)}{2(3.92 - .0166)}\right] 0.219$$

$$= 3.28 \times 10^{-5} \left[0.00876 + 0.00299\right] 0.219$$

$$= 3.28 \times 10^{-5} \left[0.01175\right] 0.219$$

$$= \underline{8.43 \times 10^{-8}}$$

Try x = 0.00568

$$K_{CO_2} = \left(\frac{0.00568}{0.99422}\right)^2 \left[\frac{3.081}{2}(.00568) + \frac{4.108(.00568)}{2(3.903)}\right] 0.219$$

$$= 3.26 \times 10^{-5} \left[0.00874 + 0.00298\right] 0.219$$

$$= 3.26 \times 10^{-5}\ (0.01172)\ 0.219 \quad = \quad \underline{8.35 \times 10^{-8}}$$

so $\quad x \quad = \quad \underline{0.00568}$

$$\therefore \quad y \quad = \quad \frac{0.00568}{3.92 - 2.92(.00568)} \quad = \quad \frac{0.00568}{3.92 - .0166}$$

$$= \quad \frac{0.00568}{3.9034} \quad = \quad \underline{0.00145}$$

$$\phi_{CO_2} \quad = \quad 3.081(0.99432)\ \frac{43.76}{2} \quad = \quad 67.1$$

$$\phi_{CO} \quad = \quad 3.081(0.00568)\ \frac{28.15}{2} \quad = \quad 0.246$$

$$\phi_{H_2O} \quad = \quad 4.108(0.99854)\ \frac{34.49}{2} \quad = \quad 70.6$$

$$\phi_{H_2} \quad = \quad 4.108(0.00145)\ 13.32 \quad = \quad 0.079$$

$$\phi_{O_2} \quad = \quad 0.01172(14.69) \quad = \quad 0.172$$

$$\phi_{N_2} \quad = \quad 19.30\left(\frac{27.87}{2}\right) \quad = \quad \underline{268.8}$$

$$\sum \phi \quad = \quad 407.00 \text{ BTU}$$

$$M_4 \quad = \quad 3.081 + 4.108 + 0.01172 + 19.3 \quad = \quad \underline{26.501} \text{ moles}$$

$$P_4 \quad = \quad \frac{26.501}{25.497} \cdot \frac{3300(1)}{591} \quad = \quad \underline{5.82} \text{ atm.}$$

Constituent	pp	ln pp	1.986(M)ln pp
$3.081(0.99432)CO_2$	0.672	-0.397	-2.415
$3.081(0.00568)CO$	0.00384	-5.56	-0.193
$4.108(0.99854)H_2O$	0.900	-0.105	-0.855
$4.108(0.00145)H_2$	0.00131	-6.63	-0.078
$0.01172\ O_2$	0.00258	-5.96	-0.139
$19.30\ N_2$	4.24	1.445	55.4

$$\sum 1.986(M)\ln pp = \underline{51.72}\ \text{BTU}$$

$$\therefore\ s_4 = 407.00 - 51.72 + \frac{3.081(.00568)121{,}200}{3300} + \frac{4.108(.00145)103{,}500}{3300}$$

$$= 407.00 - 51.72 + 0.64 + 0.19 = \underline{356.11}\ \text{BTU}$$

$\therefore$ T_4 assumed too low

Assume $T_4 = 3400\,^\circ R$

From Tables [12], $\log K_{CO_2} = -6.60$ and $\log K_{WG} = 0.616$

$$\therefore\ K_{CO_2} = 2.52 \times 10^{-7} \text{ and } K_{WG} = 4.13$$

Try x = 0.008

$$K_{CO_2} = \left(\frac{0.0082}{0.9918}\right)^2 \left[\frac{3.081(.0082)}{2} + \frac{4.108(.008)}{2(4.13 - 3.13(.0082)}\right]\frac{3400}{25.497(591)}$$

$$= 6.5 \times 10^{-5}\left[0.0123 + \frac{0.0164}{4.13 - 0.025}\right] 0.226$$

$$= 6.5 \times 10^{-5} \left[0.0123 + 0.0040\right] 0.226$$

$$= 6.5 \times 10^{-5} (0.0163)\ 0.226 = \underline{2.40 \times 10^{-7}}$$

<u>Try x = 0.0082</u>

$$K_{CO_2} = \left(\frac{0.0082}{0.9918}\right)^2 \left[\frac{3.081(.0082)}{2} + \frac{4.108(.0082)}{2(4.13 - 3.13(.0082))}\right] 0.226$$

$$= 6.84 \times 10^{-5} \left[0.0126 + 0.0041\right] 0.226$$

$$= 6.84 \times 10^{-5} (0.0167)\ 0.226 = \underline{2.58 \times 10^{-7}}$$

<u>Try x = 0.00814</u>

$$K_{CO_2} = \left(\frac{0.00814}{0.99186}\right)^2 \left[\frac{3.081(.00814)}{2} + \frac{4.108(.00814)}{2(4.13 + 3.13(.00814))}\right] 0.226$$

$$= 6.74 \times 10^{-5} \left[0.0125 + 0.0041\right] 0.226$$

$$= 6.74 \times 10^{-5} (0.0166)\ 0.226 = \underline{2.53 \times 10^{-7}}$$

So $x = \underline{\underline{0.00814}}$

$$y = \frac{0.00814}{4.13 - 3.13(.00814)} = \frac{0.00814}{4.13 - 0.0255}$$

$$= \frac{0.00814}{4.105} = \underline{\underline{0.00198}}$$

$$\Phi_{CO_2} = 3.081(.99186)22.32 = 68.2$$

$$\Phi_{CO} = 3.081(.00814)14.34 = 0.36$$

$$\Phi_{H_2O} = 4.108(.99802)17.61 = 72.2$$

$$\Phi_{H_2} = 4.108(.00198)13.58 = 0.11$$

$$\phi_{O_2} = 0.0166(14.95) = 0.25$$

$$\phi_{N_2} = 19.30(14.20) = \underline{274.0}$$

$$\sum \phi = \underline{415.12} \text{ BTU}$$

$$M_4 = 3.081 + 4.108 + 19.3 + 0.0166 = \underline{26.506} \text{ moles}$$

$$P_4 = \frac{26.506}{25.497} \cdot \frac{3400}{591} (1) = \underline{5.97} \text{ atm.}$$

Constituent	pp	ln pp	1.986(M)ln pp
$3.081(0.99185)CO_2$	0.689	-0.372	-2.26
$3.081(0.00814)CO$	0.00565	-5.17	-0.257
$4.108(0.99802)H_2O$	0.923	-0.080	-0.650
$4.108(0.00198)H_2$	0.00183	-6.30	-0.102
$0.0166\ O_2$	0.00374	-5.59	-0.184
$19.30\ N_2$	4.35	1.47	56.2
		$\sum =$	52.75 BTU

$$\therefore s_4 = 415.12 - 52.75 + \frac{3.081(.00814)121{,}200}{3400} + \frac{4.108(.00198)103{,}500}{3400}$$

$$= 415.12 - 52.75 + 0.89 + 0.32 = \underline{363.58} \text{ BTU}$$

$\therefore$ T_4 assumed too high.

By linear interpolation obtain T_4, x_4 and y_4 between 3300 and 3400 $^\circ$R.

$$\frac{DT}{357.20 - 356.11} = \frac{100 - DT}{363.58 - 357.20}$$

$$\therefore \quad DT = \frac{1.09(100)}{1.09 + 6.38} = \frac{1.09(100)}{7.47} = 14.6$$

$$\therefore \quad T_4 = 3300 + 14.6 = \underline{\underline{3315\,^\circ R}}$$

$$x_4 = 0.00568 + \frac{14.6}{100}(.00814 - .00568) = .00568 + .00036$$

$$= \underline{\underline{0.00604}}$$

$$y_4 = 0.00145 + \frac{14.6}{100}(.00198 - .00145) = .00145 + .00008$$

$$= \underline{\underline{0.00153}}$$

$$s_5 = \sum \phi_5 - \sum MR \ln pp$$

No. of moles = 3.081 + 4.108 + 19.30 = $\underline{\underline{26.489}}$ moles

<u>Try $T_5 = 2300\,^\circ R$</u>

$$\phi_{CO_2} = 3.081(16.81) = 51.9$$

$$\phi_{H_2O} = 4.108(13.22) = 54.3$$

$$\phi_{N_2} = 19.30(10.92) = \underline{210.7}$$

$$\sum \phi = \underline{316.9} \text{ BTU}$$

Constituent	pp	ln pp	1.986(M) ln pp
$3.081CO_2$	0.1162	-2.15	-13.16
$4.108H_2O$	0.1548	-1.863	-15.19
$19.3N_2$	0.729	-0.316	-12.10
		$\sum =$	-40.45 BTU

$$\therefore \; s_5 = 316.9 + 40.45 = \underline{\underline{357.35}} \text{ BTU}$$

$$\therefore \; \text{Take } T_5 = 2300^\circ R$$

$$f = \frac{V_2}{V_5} = \frac{M_1(T_1)}{M_5(CR)T_5}$$

$$= \frac{25.497(591)}{26.489(9)2300} = \underline{0.0275}$$

T_5 is found to be as assumed but f is slightly high 0.0275 rather than 0.027 as assumed so the calculations should be re-done using f = 0.0275, for greater accuracy.

<u>To determine thermal efficiency</u>

Substitute into equation 2.2-17

$$u_1 = u_{mix\ 600} - \frac{9}{20}(u_{mix\ 600} - u_{mix\ 580})$$

$$= 10{,}249 - \frac{9}{20}(10249 - 9349)$$

$$= 10{,}249 - \frac{9}{20}(900) = 10{,}249 - 405 = \underline{\underline{9{,}844}} \text{ BTU}$$

$$u_2 = \underline{\underline{107{,}105}} \text{ BTU}$$

<u>To find u_3</u>

$$u_{CO_2} = 3.081(1 - .1831)\left[53{,}963 + \frac{53.4}{200}(56{,}569 - 53{,}963)\right]$$

$$= 3.081(.8169)\left[53{,}963 + \frac{53.4}{200}(2606)\right]$$

$$= 3.081(.8169)(53{,}963 + 695) = 3.081(.8169)54{,}658$$

$$= \underline{137{,}500}$$

$$u_{CO} = 3.081(.1831)\left[29{,}287 + \frac{53.4}{200}(30{,}665 - 29{,}287)\right]$$

$$= 3.081(.1831)\ (29{,}287 + 370) = 3.081(.1831)29{,}657$$

$$= \underline{16{,}780}$$

$$u_{H_2O} = 4.108(1 - .0318\left[42{,}087 + \frac{53.4}{200}(44{,}307 - 42{,}087)\right]$$

$$= 4.108(0.9682)(42{,}087 + 592) = 4.108(.9682)42{,}679$$

$$= \underline{169{,}400}$$

$$u_{H_2} = 4.108(0.0318)\left[27{,}156 + \frac{53.4}{200}(28{,}508 - 27{,}156)\right]$$

$$= 4.108(.0318)\ (27{,}156 + 361) = 4.108(.0318)27{,}517$$

$$= \underline{3{,}580}$$

$$u_{O_2} = 0.3465\left[31{,}115 + \frac{53.4}{200}(32{,}622 - 31{,}115)\right]$$

$$= 0.3465\ (31{,}115 + 401) = 0.3465(31{,}516)$$

$$= \underline{10{,}900}$$

$$u_{N_2} = 19.30\left[28{,}961 + \frac{53.4}{200}(30{,}337 - 28{,}961)\right]$$

$$= 19.30\ (28{,}961 + 367) = 19.3(29{,}328)$$

$$= \underline{566{,}000}$$

$$u_3 = \underline{\underline{904{,}160}}\ \text{BTU}$$

<u>To find u_4</u>

$$u_{CO_2} = 3.081(1 - .00604)\left[29{,}750 + \frac{15}{100}(30{,}991 - 29{,}750)\right]$$

$$= 3.081(0.99395)\ (29{,}750 + 186) = 3.081(.99395)29{,}936$$

$$= \underline{92{,}900}$$

$$u_{CO} = 3.081(.00604)(16{,}414 + 100) = 3.081(.00604)16{,}514$$

$$= \underline{308}$$

$$u_{H_2O} = 4.108(.99847)(22{,}066 + 149) = 4.108(.99847)22{,}215$$

$$= \underline{91{,}300}$$

$$u_{H_2} = 4.108(.00153)(14{,}921 + 91) = 4.108(.00153)15{,}012$$

$$= \underline{94}$$

$$u_{O_2} = \left[\frac{3.081}{2}(.00604) + \frac{4.108}{2}(.00153)\right](17{,}386 + 104)$$

$$= (0.00933 + 0.00314)(17{,}490) = 0.01247(17{,}490)$$

$$= \underline{218}$$

$$u_{N_2} = 19.30\ (16{,}199 + 98) = 19.30(16{,}297) = \underline{316{,}300}$$

$$u_4 = \underline{\underline{501{,}120\ \text{BTU}}}$$

$$\therefore \quad \eta = \frac{(904{,}160 - 501{,}120) - (107{,}105 - 9{,}844)}{44.094(19{,}929)} \cdot 100$$

$$= \frac{(403{,}040 - 97{,}261)}{44.094(19{,}929)} \cdot 100$$

$$= \frac{(305{,}779)100}{44.094(19{,}929)} = \underline{\underline{34.7\%}}$$

<u>To find m.e.p.</u>

Substitute into equation 2.2-16

$$v_1 = \frac{mRT_1}{P_1} = \frac{25.497(1545)591}{14.7(144)} = 110{,}000\ \text{ft}^3$$

$$v_2 = \frac{v_1}{CR} = \frac{\underline{110,000}}{9} = 12,200 \text{ ft}^3$$

$$\therefore \quad \text{m.e.p.} = \frac{305,770(778)}{(110,000 - 12,200)(144)} = \frac{305,779(778)}{97,800(144)}$$

$$= \underline{\underline{169}} \text{ psi.}$$

APPENDIX B

PROGRAM FOR THEORETICAL ANALYSIS

```
$JOB              525015   G.R. POND
$TIME             30,3000
$IBJOB POND
$IBFTC POND       NODECK
C   ** OTTO CYCLE CALCULATIONS  **
C
      DATA FU1,FU2/5HC8H18,4HC3H8/
      REAL N2,NP,LS,MCO,MCO2,MOS,MW,MO2
      KI=1
      READ(5,51) XC
      IF(XC.GT.4.) GO TO 2
      FU=FU2
      XC=3.
      XH=8.
      CR=8.0
      CEF=878822.
      HEAT=44.098*19929.
      UCG=180.0
      GO TO 4
  2   KI=2
      FU=FU1
      XC=8.
      XH=18.
      CR=7.0
      CEF=2201618.
      HEAT=236?226.
      UCG=674.0
  4   XH2=XH/2.0
      XO2=(XH2+2.0*XC)/2.
      XN2=3.76*XO2
      WRITE(6,52) FU
  6   PC=0.80
      TT1=920.
      TT2=1350.
      F=0.03
      CZ=XH2
      WRITE(6,54) CR
      M=1
      N=15
      DO 11 J=M,N
      LI=0
      PE=100.*PC
      WRITE(6,53) PE
      MOS=PC*XO2
      IF(PC.LT.0.999) GO TO 8
C
C  IF EXCESS AIR OR 100 PERCENT AIR
      MO2=XC
      MCO=0.000
      MCO2=XC
      IF(PC.LT.1.001) GO TO 12
```

```
      EXC=(2.*XO2*PC-2.*MO2-XH2)/2.
      GO TO 14
C
C IF AIR LESS THAN 100 PERCENT CO2 DISSOC TO CO
   8  MOS=PC*XO2
      MO2=MOS-XH/4.
      MCO=2.0*(XC-MO2)
      IF(MCO.GE.0.0000) GO TO 10
      MCO=0.00000
  10  MCO2=MO2-MCO/2.
  12  EXC=0.000000000
C
  14  CONTINUE
      PO2=PC*XO2
      PN2=PC*XN2
      XLS=1.00+PO2+PN2
      MW=XC*12.0+XH*1.008
C
C  INITIAL COND@S  TO FIND T1 - FUEL MIXTURE PLUS CLEARANCE GAS
C   ASSUME FUEL TEMP = 537.
C ** CONSTANT PRESSURE ADIABATIC PROCESS **
C  U1 = FU5+HCG+HGF-PV/J+Q    ASSUME Q=0.0
      FA=MW/(32.0*PO2+28.0*PN2)
      HCG=PO2*83.0+PN2*81.0+(XLS-1.0)*1066.0
      HG=UCG+1066.0
C
C  CXHY+PC*(XO2+XN2)=MCO2*CO2+XH2*H2O+MCO*CO+XN2*PC*N2+EXC*O2
C
C   FIRST TRIAL ASSUMING NO DISSOCIATION AND FOLLOWING
      T1=TT1+80.
      T2=TT2+180.
      T4=3600.
      T5=2500.
      X=0.0
      Y=0.0
      LF=0
      LK=0
      AZ=MCO2
      BZ=MCO
      DZ=EXC
      EZ=PN2
  16  MCO2=AZ
      MCO=BZ
      XH2=CZ
      EXC=DZ
      PN2=EZ
C
C   SUM OF MOLES ON RIGHT SIDE OF EQUATION (PRODUCTS)
      Z=1.+F
      ZA=MCO2*Z
      ZB=MCO*Z
      ZC=XH2*Z
      ZD=EXC*Z
      ZE=PN2*Z
      MCO2=ZA
      MCO=ZB
```

```
      XH2=ZC
      EXC=ZD
      PN2=ZE
   13 XRS=XH2+MCO+EXC+PN2+MCO2
C
C   NO. OF MOLES IN CHARGE
   15 XCH=XRS-1.
      WRITE(6,60) MCO2,MCO,XH2,EXC,PN2,XRS,XCH,ZA,AZ
      KO=0
   17 CALL ENERGY (T5,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFU)
      UA=MCO2*(X*UCO+(1.00000-X)*UCO2)
      UB=XH2*(Y*UH2+(1.00000-Y)*UH2O)
      UC=(X*MCO2/2.0+Y*XH2/2.+EXC)*UO2
      UD=PN2*UN2+MCO*UCO
C
C   P(V1-V0)=RT(V1-V0) =RT/V1(V1-V2) =RT(1-1/CR)
      FUH=F*(UA+UB+UC+UD)+HCG+HG
      R=1.9859*XCH*(1.0-1.0/CR)
   18 U1=FUH-R*T1
C
C   CHECK U1 BY CONSIDERING GAS AT T1
C    USENS=F*UCL+(UAIR+UFU)
C
      CALL ENERGY (T1,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFU)
      UA=MCO2*(X*UCO+(1.00000-X)*UCO2)
      UB=XH2*(Y*UH2+(1.00000-Y)*UH2O)
      UC=(X*MCO2/2.0+Y*XH2/2.+EXC)*UO2
      UD=PN2*UN2+MCO*UCO
      UE=PO2*UO2+PN2*UN2+UFU
      USENS=UE+(UA+UB+UC+UD)*F
      PT1=T1
      CALL TEMP(T1,USENS,U1,DIF,KO)
      TT=ABS((PT1-T1)/T1)
      IF(TT.GT.0.01) GO TO 17
      IF(KO.LT.2.OR.DIF.GT.0.0) GO TO 18
      V2=V1/CR
      V1=1545.*T1*XCH/(144.*14.7)
      KO=0
C
C    ADIABATIC COMPRESSION TO T2  - AT CONSTANT ENTROPY
C
C    ENTROPY OF FUEL
   20 IF(XC.LT.4.) GO TO 22
      SFU=5.93*ALOG(T2/T1)+0.061*(T2-T1)
      GO TO  24
   22 SFU=0.272*ALOG(T2/T1)+.0320*(T2-T1)-(543.*(T2**2.0-T1**2.0)/200000
     1000.)
C
   24 A=1.0/T2
      B=1.0/T1
      SCO2=F*MCO2*(1.-X)*(14.3*ALOG(T2/T1)+6530.*(A-B)-705000.*(A**2.0-B
     1**2.0))
      SCO=F*(MCO+MCO2*X)*(7.47*ALOG(T2/T1)+3290.*(A-B)-535000.*(A**2.0-B
     1**2.0))
```

```
      SO2=(MOS+F*(EXC+X*MCO/2.+Y*XH2/2.))*(9.529*ALOG(T2/T1)+173.0*2.0*
     1(A**0.5-B**0.5)-1530.0*(A-B))
      SH2O=F*XH2*(1.-Y)*(17.87*ALOG(T2/T1)+597.*2.*(A**0.5-B**0.5)-7500.
     1*(A-B))
      SN2=PN2*(1.0+F)*(7.48*ALOG(T2/T1)+3470.*(A-B)-580000.*(A**2.-B**2.
     1))
      SH2=F*XH2*Y*(3.77*ALOG(T2/T1)+0.000578*(T2-T1)-40.*(A**0.5-B**0.5)
     1)
      SUM=SFU+SCO2+SCO+SO2+SN2+SH2O+SH2
      SU=XCH*1.9859*ALOG(CR)
C
      PT2=T2
   26 CALL TEMP (T2,SUM,SU,DIF,KO)
      P2=CR*1.0*T2/T1
      IF(KO.LT.2.OR.DIF.GT.0.0) GO TO 20
      CALL ENERGY(T2,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFU)
      UA=MCO2*UCO2
      UB=XH2*UH2O
      UC=EXC*UO2
      UD=PN2*UN2+MCO*UCO
      UE=PO2*UO2+PN2*UN2+UFU
      U2=F*(UA+UB+UC+UD)+UE
      LS=U2+CEF
      CALL CBUSTN (XC,LS,PC,MCO2,XH2,PN2,EXC,MCO,X3,Y3,T3,KL,T2,P2,XCH,X
     1M)
      XC3=XRS+XM
C
C  REVERSIBLE ADIABATIC EXPANSION -T3 TO T4 - AT CONSTANT ENTROPY
C     X AND Y  BOTH DECREASE DUE TO TEMPERATURE DROP
C
C  ENTROPY AT T3
      PP3=P3
      P3=XC3*T3*P2/(XCH*T2)
   27 CALL ENTROP(T3,X3,Y3,MCO2,MCO,EXC,XH2,PN2,P3,XC3,S3)
      V3=XC3*1545.*T3/(P3*14.7*144.)
      V4=CR*V3
C
C  TO FIND T4
   28 LS=0.0
      PT4=P4
      KO=0
      LL=18
   29 IF(T4.GT.3000.) GO TO 30
      X4=0.0
      Y4=0.0
      XM=0.0
      TT4=T4-10.
      T4=TT4
      GO TO 31
   30 KL=LL+1
      CALL CBUSTN (XC,LS,PC,MCO2,XH2,XN2,EXC,MCO,X4,Y4,T4,KL,T1,P3,XCH,X
     1M)
   31 LL=KL
```

```
C   TO FIND P4
      XCH4=XRS+XM
      P4=XCH4*T4/(XCH*T1)
      PS4=S4
      CALL ENTROP(T4,X4,Y4,MCO2,MCO,EXC,XH2,PN2,P4,XCH4,S4)
      IF(S4.GT.S3) GO TO 29
      IT=100.*(S3-S4)/(PS4-S4)
      KT=T4
      T4=IT+KT+10
   33 CALL ENTROP(T4,X,Y,MCO2,MCO,EXC,XH2,PN2,P4,XCH4,S4)
      IF(T4.LT.1000.) GO TO 35
      KO=2
      CALL TEMP(T4,S4,S3,DIF,KO)
      IF(DIF.GT.0.0) GO TO 33
   35 CONTINUE
C
C    EXHAUST PROCESS AND CLEARANCE GAS
      V4=XCH4*1545. *T4/(P4*144.*14.7)
      DV=V4-V1
      IF(ABS(DV).LT.50.) GO TO 32
C
C   ISENTROPIC EXPANSION TO T5 AT 14.7 PSI
C    ASSUMING NO DISSOCIATION AT T5
   32 P5=1.00
      PT5=T5
      X5=0.0
      Y5=0.0
      T5=PT5+250.
      XCH5=XRS
      KO=0
   38 CALL ENTROP(T5,X5,Y5,MCO2,MCO,EXC,XH2,PN2,P5,XCH5,S5)
      CALL TEMP(T5,S5,S3,DIF,KO)
      IF(KO.LT.2.OR.DIF.GE.0.0) GO TO 38
      TT=ABS((PT5-T5)/T5)
      IF(TT.LT.0.01) GO TO 39
      IT1=T1
      T1=IT1+50
      GO TO 17
   39 V5=XCH5*1545.*T5/(14.7*144.)
      FF=T1*XCH/(CR*T5*XCH5)
      DF=ABS((F-FF)/FF)
      LF=1
      GF=V2/V5
      F=FF
      IF(DF.LT.0.01) GO TO 40
      IT1=T1
      T1=IT1+50
      GO TO 16
C
C    TO FIND THERMAL EFFIC. AND BMEP
   40 CALL ENERGY (T3,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFU)
      WRITE(6,65) PE,T1,T2,P2,T3,P3,T4,P4,X3,Y3,X4,Y4,F
      UA=MCO2*(X3*UCO+(1.00000-X3)*UCO2)
      UB=XH2*(Y3*UH2+(1.00000-Y3)*UH2O)
      UC=(X3*MCO2/2.0+Y3*XH2/2.+EXC)*UO2
      UD=PN2*UN2+MCO*UCO
```

```
      U3=UA+UB+UC+UD
      CALL ENERGY (T4,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFU)
      UA=MCO2*(X4*UCO+(1.00000-X4)*UCO2)
      UB=XH2*(Y4*UH2+(1.00000-Y4)*UH2O)
      UC=(X4*MCO2/2.0+Y4*XH2/2.+EXC)*UO2
      UD=PN2*UN2+MCO*UCO
      U4=UA+UB+UC+UD
      WORK=U3-U4+U1-U2
      ETA=100.*WORK/HEAT
      V1=XCH*1545.*T1/(14.7*144.)
      V2=V1/CR
      BMEP=WORK*778./(144.*(V1-V2))
      WRITE(6,57) U1,U2,U3,U4,WORK,ETA,V1,BMEP
      TT1=T1
      TT2=T2
      TT4=T4
      TT5=T5
      DPC=PC+0.10
      PC=DPC
   11 CONTINUE
      PCR=CR
      CR=PCR+1.0
      IF(CR.LE.11.0) GO TO 6
      GO TO(2,99),KI
   51 FORMAT(F6.0)
   52 FORMAT(1H1,40X,8H FUEL IS,2X,A6)
   53 FORMAT(1HK,15X,13H PERCENT AIR=,F7.2)
   54 FORMAT(1HJ,20X,20H COMPRESSION RATIO =,F7.2)
   57 FORMAT(1H ,8F16.2)
   60 FORMAT(1HJ,6F15.4,3F12.4)
   65 FORMAT(1HK,9F9.2,5F10.6)
   99 STOP
      END


$IBFTC ENTROP  DECK
      SUBROUTINE ENTROP(T3,X,Y,MCO2,MCO,EXC,XH2,PN2,P,XC,S)
      REAL MCO2,MCO
      T=520.0
      A=1.0/T3
      B=1.0/520.0
      IF(T3.LE.600.) WRITE(6,59) T3,X,Y,MCO2,MCO,EXC,XH2,P,XC
      TLOG=ALOG(T3/T)
      SCO2=MCO2*(1.-X)*(16.2*TLOG+6530.*(A-B)-705000.*(A**2.0-B**2.0))
      SCO=(MCO+MCO2*X)*(9.46*TLOG+3290.*(A-B)-535000.*(A**2.0-B**2.0))
      SO2=(EXC+X*MCO2/2.+Y*XH2/2.)*(11.515*TLOG+173.0*2.0*(A**0.5-B**0.5
     1)-1530.*(A-B))
      SH2O=XH2*(1.-Y)*(19.86*TLOG+597.*2.*(A**0.5-B**0.5)-7500.*(A-B))
      SN2=PN2*(9.47*TLOG+3470.*(A-B)-580000.*(A**2.-B**2.))
      SH2=XH2*Y*(5.76*TLOG+0.000578*(T3-T)-40.*(A**0.5-B**0.5))
      IF(T3.LE.4000.) GO TO 27
      EH2=SH2-0.00033*((T3-T)-4000.*TLOG)*XH2*Y
      SH2=EH2
      IF(T3.LE.5000.) GO TO 27
      EO2=SO2+0.00005*((T3-T)-4000.+TLOG)*(EXC+X*MCO2/2.+Y*XH2/2.)
```

```
      SO2=EO2
   27 SUM=SCO2+SCO+SO2+SN2+SH2O+SH2
C
C   TO FIND PARTIAL PRESSURES OF CONSTITUENTS AT T3
      A=(1.0-X)*MCO2
      B=(EXC+X*MCO2/2.+Y*XH2/2.)
      C=(1.00-Y)*XH2
      D=(MCO+MCO2*X)
      E=PN2
      G=XH2*Y
      AP=A*P/XC
      BP=B*P/XC

      CP=C*P/XC
      DP=D*P/XC
      EP=E*P/XC
      GP=G*P/XC
C    SUM OF 1.9859(M)LN(PP)
      IF(AP.LE.0.0) GO TO 21
      SA=A*ALOG(AP)
      GO TO 22
   21 SA=0.0
   22 IF(CP.LE.0.0) GO TO 23
      SC=C*ALOG(CP)
      GO TO 24
   23 SC=0.0
   24 IF(EP.LE.0.0) GO TO 25
      SE=E*ALOG(EP)
      GO TO 26
   25 SE=0.0
   26 IF(BP.LE.0.0) GO TO 28
      SB=B*ALOG(BP)
      GO TO 29
   28 SB=0.0
   29 IF(DP.LE.0.0) GO TO 31
      SD=D*ALOG(DP)
      GO TO 32
   31 SD=0.0
   32 IF(GP.LE.0.0) GO TO 33
      SG=G*ALOG(GP)
      GO TO 34
   33 SG=0.0
   34 SUS=1.9859*(SA+SB+SC+SD+SE+SG)
      SDIS=(MCO2*X*121181.+XH2*Y*103486.)/T3
      S=SUM-SUS+SDIS
      RETURN
   59 FORMAT(1H ,8F16.2)
      END
```

```
$IBFTC ENERGY  DECK
      SUBROUTINE ENERGY(T,XC,UCO2,UCO,UO2,UN2,UH2O,UH2,UFU)
C   UT-U520=INTEGRAL OF CV*DT =INT(CV*(T-520))     CV=CP-1.9859
      TE=T-520.0
      R=1.0/T
      S=1.0/520.0
      V=T**2.0
      W=520.0**2.0
      X=T**0.5
      Y=520.0**0.5
      UCO2=(16.2-1.9859)*TE-6530.*ALOG(T/520.)-141.*(R-S)*10000.
      UCO=(9.46-1.9859)*TE-3290.*ALOG(T/520.)-107.*(R-S)*10000.
      UO2=(11.515-1.9859)*TE-173.*2.*(X-Y)+1530.*ALOG(T/520.)
      UN2=(9.47-1.9859)*TE-3470.*ALOG(T/520.)-116.*(R-S)*10000.
      UH2O=(19.86-1.9859)*TE-597.*2.*(X-Y)+7500.*ALOG(T/520.)
      UH2=(5.76-1.9859)*TE+0.578*(V-W)/2000.+40.*(X-Y)
      IF(XC.LT.4.0) GO TO 1
      UFU=(7.92-1.9859)*TE+0.0601*(V-W)/2.0
      GO TO 3
    1 UFU=(2.258-1.9859)*TE+.032*(V-W)/2.-543.*((T/100.)**3.-5.2**3.)/30
     10.
    3 IF(T.LE.4000.) GO TO 2
      UH=UH2-.33*(.5*T**2.-4000.*T)/1000.
      UH2=UH
      IF(T.LE.5000.) GO TO 2
      UO=UO2+.05*(.5*T**2.-4000.*T)/1000.
      UO2=UO
  2   RETURN
      END
```

```
$IBFTC TEMP    DECK
      SUBROUTINE TEMP(T,SUM,SU,DIF,KO)
      DIF=SUM-SU
      TE=T
      IF(KO.GT.0) GO TO 2
      IF(DIF.LT.0.0) GO TO 2
      IT=(T+5.0)/10.
      TE=IT*10
      DT=-100.
      GO TO 3
    2 IF(KO.EQ.1.AND.DIF.GT.0.0) GO TO 5
      IF(KO.EQ.2) GO TO 6
      KO=1
      DT=10.
      DI=DIF
      GO TO 3
    5 KO=2
    6 DT=-1.00
      DI=DIF
    8 T=TE+DT
      RETURN
      END
```

```
$IBFTC CBUSTN  NODECK
      SUBROUTINE CBUSTN (XC,LS,PC,MCO2,XH2,PN2,EXC,MCO,XX,YY,T,KL,T2,P2,
     1XCH,XM)
C
C  DISSOCIATION OF CO2 AND H2O ONLY
C
      DIMENSION  TEPR(25),O2(25),N2(25),CO2(25),H2O(25),H2(50),CO(25),
     1LKCO2(25),LKWG(25),KCO2(25),KTCO2(25),X(25),Y(25)
      REAL N2,LKCO2,LKWG,MP,KCO2,KTCO2,KWG,LS,MO2,MCO,MCO2,MOS
      INTEGER TEPR
      IF(LS.EQ.0.0) GO TO 4
      IF(KL.GT.0) GO TO 2
      DO 3 I=1,23
      READ(5,20) TEPR(I),LKCO2(I),LKWG(I)
      KL=1
   3  CONTINUE
  2   IL=1
  1   I=IL
C  CHEMICAL ENERGY OF DISSOC OF H2O AND CO2
      CEH2=103486.*XH2
      CECO=121181.*MCO2
C
C  SUMMATION OF TERMS IN ENERGY EQN.
      TEMPR=TEPR(I)
      CALL ENERGY (TEMPR,XC,CO2(I),CO(I),O2(I),N2(I),H2O(I),H2(I),UFU)
      IF(EXC.GT.0.001) GO TO 30
      UO2=0.0000
      GO TO 31
  30  UO2=EXC*O2(I)
  31  IF(MCO.GT.0.001) GO TO 32
      UCO=0.000000
      GO TO 33
  32  UCO=MCO*CO(I)
  33  SUMN=MCO2*CO2(I)+XH2*H2O(I)+PN2*N2(I)+EXC*O2(I)+UO2+UCO
      SUMX=MCO2*CO(I)-MCO2*CO2(I)+(MCO2/2.0)*O2(I)+CECO
      SUMY=XH2*H2(I)-XH2*H2O(I)+(XH2/2.)*O2(I)+CEH2
      A=LS-SUMN
      IF(A.GE.0.001) GO TO 34
      IL=I+1
      GO TO 1
  34  B=A/SUMY
  35  C=SUMX/SUMY
C  OBTAIN LOG KWG FROM TABLES
      KWG=10.0000**LKWG(I)
      D=KWG-1.000
C  KWG=X(1-Y)/Y(1-X)  SO Y=X/(KWG-(KWG-1)X) SO Y=X/(KWG-D*X)
C
C  EQUATE Y@S  (B-C*X)*(KWG-D*X)=X
      CC=B*KWG
      AA=C*D
      BB=B*D+C*KWG+1.000
      DD=BB**2-4.000*AA*CC
      X(I)=(BB-SQRT(DD))/(2.000*AA)
      Y(I)=X(I)/(KWG-D*X(I))
C  TO FIND KCO2=((P@CO2)**2)*(P@O2)/(P@CO2)**2
C  NO OF MOLES OF PRODUCTS =MP
```

```
      MP=MCO2+XH2+MCO+EXC+PN2+(MCO2*X(I)+XH2*Y(I))/2.0
      R=X(I)**2
      S=(1.0000-X(I))**2
      W=(MCO2/2.)*X(I)+(XH2/2.0)*Y(I)
      TEMPER=TEPR(I)
      KCO2(I)=(R*TEMPER*W*P2)/(S*XCH*T2)
      KTCO2(I)=10.000**LKCO2(I)
      IL=I+1
      IF(I.EQ.23) GO TO 12
      IF(LS.GT.0.0) GO TO 6
4     I=KL
      KO=0
      XX=0.06
      WX=7000.*XX
      KWG=10.00**LKWG(I)
      D=KWG-1.00
      KTCO2(I)=10.00**LKCO2(I)
      T=TEPR(I)
 5    YY=XX/(KWG-D*XX)
      IF(XX.GT.0.1) GO TO 14
      IF(XX.GE.0.00015) GO TO 11
      XX=0.0001
      YY=0.00001
11    A=XX**2.0
      B=(MCO2*XX+XH2*YY)/2.0
      D=(1.0-XX)**2.0
      KCO2(I)=B*T*A/(D*T2*XCH)
      CK=10000000.*KCO2(I)
      TK=10000000.*KTCO2(I)
      CALL TEMP(WX,CK,TK,DIF,KO)
      XX=WX/7000.
      IF(KO.LT.2.OR.DIF.GT.0.0) GO TO 5
      GO TO 14
6     IF(KCO2(I).GT.KTCO2(I)) GO TO 8
      IF(T.LE.3000.) GO TO 14
      PT=TEPR(I)
      PX=X(I)
      PY=Y(I)
      PK=KCO2(I)
      PKT=KTCO2(I)
      PKW=KWG
      PMP=MP
      GO TO 1
8     F=KCO2(I)-KTCO2(I)
      WRITE(6,21) TEPR(I),SUMN,SUMX,SUMY,MP,KCO2(I),KTCO2(I),X(I),Y(I)
      IF(I.GT.1) GO TO 10
      KL=2
      T=5400.
      XX=X(I)
      YY=Y(I)
      WRITE(6,27)
      GO TO 14
10    G=PKT-PK
```

```
      IF(TEPR(I).LT.5000) GO TO 7
      SPA=200.
      GO TO 9
    7 SPA=100.
    9 IT=F*SPA/(F+G)
      DT=IT
      TT=TEPR(I)
      T=TT+DT+5.0
      U=X(I)-PX
      XX=PX+(SPA-DT)*U/SPA
      V=Y(I)-PY
      YY=PY+(SPA-DT)*V/SPA
      DMP=PMP-MP
      XMP=MP+DMP*DT/SPA
      MP=XMP
      GO TO 14
   12 WRITE(6,25)
      KL=2
   14 XM=(MCO2*XX+XH2*YY)/2.0
      RETURN
   20 FORMAT(I4,F6.2,F7.3)
   21 FORMAT(1HJ,I5,3F12.0,F8.3,4F14.7)
   25 FORMAT(1HJ,44H TEMPERATURE BELOW 3000@R MORE DATA REQUIRED)
   27 FORMAT(1HJ,14H T3 ABOVE 5400)
      END
$ENTRY          POND
    3.
5400 -0.94  0.840
5200 -1.32  0.829
5000 -1.70  0.816
4900 -1.90  0.810
4800 -2.12  0.803
4700 -2.36  0.795
4600 -2.59  0.787
4500 -2.83  0.779
4400 -3.08  0.770
4300 -3.35  0.760
4200 -3.63  0.748
4100 -3.93  0.736
4000 -4.25  0.723
3900 -4.59  0.709
3800 -4.95  0.693
3700 -5.32  0.676
3600 -5.72  0.658
3500 -6.15  0.638
3400 -6.60  0.616
3300 -7.08  0.593
3200 -7.58  0.570
3100 -8.12  0.545
3000 -8.68  0.520
```

Variable(s) FUEL-AIR RATIO AND SPARK | Range CR = 9.82 | Time Start 12:15 Finish 1:45

Barometric Pressure 27.480 | Ambient Temp. 82 °F | Wet Bulb °F | R. H. %

Cooling Water Temp. Start 208 °F, Finish 208 °F | Oil Temp. Start 140 °F, Finish 140 °F | Oil Pressure 36

Special Test Equipment

Oscilloscope Settings

μ strain Rotan

Heating Value of Fuel 19,929 BTU/lb | Orifice Size Coef. | Dynamometer Arm

R.P.M.				Fuel			Intake Air			Exhaust Gas				Dynamometer
Run No.	Spark Set	Revs.	Time	Cons.	Temp.	Pres.	Temp.	Δ P	Manif.	Temp.	CO_2	O_2	CO	Load
48	5	1116	1.849		78	8.00	82	0.217		803	7.0	2.2	6.4	23.8 Lbs.
49	5	1280	2.116		79	6.00	84	0.214		856	9.4	1.7	3.9	24.9 Lbs.
50	5	1518	2.554		79	4.00	84	0.214		830	11.3	2.5	0.1	23.4 Lbs.
51	10	1934	3.233		80	7.22	85	0.220		703	9.0	6.0	0.0	17.5 Lbs.
52	20	2387	4.001		80	1.20	85	0.225		535	8.5	6.9	0.0	9.2 Lbs.

Test Crew Duty

FRICTION LOAD = 9.7 Lbs.

Recorder's Signature ____________ Instructor ____________

APPENDIX D

SAMPLE CALCULATION OF TEST RESULTS

Test No. 5, Run 43

C.R. = 9.77

Spark 20°

Revs 2333

Time 3.845

Fuel Temp. 78 °F

Fuel Pressure 2 x 0.68 = 1.32" H_2O

Air Temp. 83 °F

Air-flow Manometer 0.227 in. H_2O

Barometric Pressure = 27.590 in.Hg.

Cylinder Temp. 585 °F

% CO_2 8.4

% O_2 7.4

% O 0.0

Dyna. Load 10.9 lbs.

Fric. Load 10.1 lbs.

Gas Pressure: $\dfrac{1.32\ (29.92)}{33.899\ (12)} = 0.0971$ in.Hg.

$$\text{Saturation Pressure} = \left[.3631 + 8(.01438)\right] \frac{29.92}{14.696}$$

$$= \left[.3631 + .1150\right] \frac{29.92}{14.696}$$

$$= (0.4781)\ \frac{29.92}{14.696} = 0.973 \text{ in.Hg.}$$

$$P = 27.590 + 0.971 - 0.973 = 26.714 \text{ in Hg.}$$

0.500 cu. ft. of gas in 3.845 mins.

Correct for Barometric conditions.

$$\text{Vol.} = \frac{.5(26.714)520}{29.92(460+78)} = .431 \text{ ft}^3$$

$$\text{Wt.} = \frac{.431(60)}{8.503(3.845)} = 0.791 \text{ lb/hr.}$$

$$\text{Correction factor (CF)} = \frac{29.90}{27.590}\sqrt{\frac{460 + 78}{545}}$$

$$= \frac{29.90}{27.59}\sqrt{0.989} = 1.078$$

$$\text{r.p.m.} = \frac{2333}{3.845} = 606 \text{ r.p.m.}$$

$$\text{Torque} = \frac{10.52}{12}(10.9) = 9.56 \text{ ft-lb.}$$

$$\text{BHP} = \frac{2\pi(9.56)606}{33{,}000} = 1.103 \text{ HP}$$

$$\text{FHP} = 2\pi\left(\frac{10.52}{12}\right)\frac{10.1(606)}{33{,}000} = 1.022 \text{ HP}$$

$$\text{CIHP} = 1.078\ (1.103 + 1.022)$$

$$= 1.078\ (2.125) = 2.29 \text{ HP}$$

$$\text{C.B.H.P.} = 2.29 - 1.022 = 1.27 \text{ HP}$$

$$\text{Thermal Effic.}(\eta) = \frac{2.29(2545)100}{19929(.791)} = 37.9\%$$

$$\text{Brake Thermal Effic.} = \frac{1.27(2545)100}{19929(.791)} = 20.5\%$$

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

$$\text{Mech. Efficiency} = \frac{1.27}{2.29}(100) = 55.5\%$$

$$\text{Fuel/CIHP} = \frac{.791}{2.29} = 0.346 \text{ lb/CIHP}$$

$$\text{Fuel/BHP} = \frac{.791}{1.27} = 0.623 \text{ lb/BHP}$$

$$\text{Air Density} = \frac{27.590(14.696)144}{29.92\ (538)\ 53.34} = .0679 \text{ lb/ft}^3$$

$$\text{Head of air} = \frac{.227(62.4)}{.0679\ (12)} = 17.4 \text{ ft. of air}$$

$$\text{Velocity} = 0.62\sqrt{64.4(17.4)}$$

$$= 0.62(33.45) = 20.75 \text{ f.p.s.}$$

$$\text{Flow of air} = \left[\frac{20.75\ \pi(.9983)^2\ 60(.0679)}{4(144)}\right]1.078$$

$$= \left[\frac{20.75\ \pi(.9966)60(.0679)}{4(144)}\right]1.078$$

$$= 0.495 \text{ lb/min.}$$

$$\text{Fuel-air Ratio} = \frac{0.791}{0.495(60)} = 0.0266 \text{ lb.fuel/lb.air}$$

$$\text{Air-fuel Ratio} = \frac{1}{.0266} = 37.6 \text{ lb.air/lb.fuel}$$

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

$$\text{B.m.e.p.} = \frac{33{,}000(1.27)4(2)}{\pi(3.25)^2(.375)606} = 44.4 \text{ psi}$$

$$\text{I.m.e.p.} = \frac{33{,}000(2.29)4(2)}{\pi(3.25)^2(.375)606} = 80.1 \text{ psi}$$

[illegible]

[illegible]

APPENDIX E

PROGRAM FOR CALCULATION OF TEST DATA

```
$JOB            525015   G.R. POND
$TIME           5,3000
$IBJOB POND
$IBFTC POND     DECK
C  CALCULATIONS FOR C.F.R. ENGINE TEST
      DIMENSION RUN(50),REVS(50),TIME(50),TEMP(50),DP(50),TEM(50),CO2(50
     1),O2(50),CO(50),LOAD(50),FRIC(50),RPM(50),LB(50),TOR(50),BHP(50),E
     2TA(50),FHP(50),IHP(50),MEFF(50),FU(50),RATIO(50),Z(50),E(50),FA(50
     3),BMEP(50),AIR(50),CBHP(50),CMEP(50),FUEL(20),SET(50),CF(50),CR(2
     40),BAPRES(20),TEST(20),SPARK(50),KNOCK(50),FUE(20),TE(50),AF(50),
     5HYC(50),FUA(50),COM(50),MEN(50),TS(50),FUIHP(50),CYTEM(50),FUTEM(5
     60),PRES(50)
      REAL LOAD, LB,IHP,N2,MASS,MEFF,MW,MEN
      INTEGER RUN,NO,I
      DD=500.0
      READ(5,99) M, PROPA
      DO 24 J=1,M
      READ(5,100)BAPRES(J),CR(J),TEST(J),NO,FRIC(J),FUEL(J),FUE(J)
      WRITE(6,104)
      WRITE(6,105)TEST(J),CR(J),FUEL(J),FUE(J),BAPRES(J),NO
      DO 1 I=1,NO
      READ(5,106)RUN(I),SPARK(I),REVS(I),TIME(I),FUTEM(I),PRES(I),TEMP(I
     1),DP(I),TEM(I),CO2(I),O2(I),CO(I),LOAD(I),COM(I),MEN(I),TS(I)
      RPM(I)=REVS(I)/TIME(I)
    1 CONTINUE
      IF(FUEL(J).EQ. PROPA) GO TO 3
      WRITE(6,102)
      DO 2 I=1,NO
    2 WRITE(6,111) RUN(I),SPARK(I),REVS(I),TIME(I),TEMP(I),DP(I),TEM(I),
     1CO2(I),O2(I),CO(I),LOAD(I),COM(I),MEN(I),TS(I)
      GO TO 5
    3 WRITE(6,103)
      DO 4 I=1,NO
    4 WRITE(6,112) RUN(I),SPARK(I),REVS(I),TIME(I),FUTEM(I),PRES(I),TEMP
     1(I),DP(I),TEM(I),CO2(I),O2(I),CO(I),LOAD(I),COM(I),MEN(I),TS(I)
    5 CONTINUE
      WRITE(6,113) FRIC(J)
      PRESS=(BAPRES(J)*14.696)/29.92
      IF(FUEL(J).EQ. PROPA) GO TO 7
C  FUEL IS GASOLINE
      X=7.
      Y=16.
      HV=19157.
      MW=100.198
      STOIC=0.068
      DO 6 I=1,NO
C  FUEL CONSUMPTION (50 GRAMS)
      LB(I)=(0.050*2.2046*60.)/TIME(I)
    6 CONTINUE
      GO TO 11
```

```
C   FUEL IS PROPANE GAS
    7  X=3.
       Y=8.
       HV=19929.
       MW=44.098
       STOIC=0.064
       DO 10 I=1,NO
C   FUEL CONSUMPTION IS 1/2 CUBIC FOOT
       GAPR=2.*PRES(I)*29.92/(33.899*12.0)
       IF(FUTEM(I).GT.70.) GO TO 8
       PSAT=(0.3631-(70.-FUTEM(I))*0.01068)*29.92/14.696
       GO TO 9
    8  PSAT=(0.3631+(FUTEM(I)-70.)*0.01438)*29.92/14.696
    9  PT=BAPRES(J)+GAPR-PSAT
       VOL=0.5*PT*520./(29.92*(FUTEM(I)+459.9))
       LB(I)=60.0*VOL/(8.503*TIME(I))
   10  CONTINUE
   11  CONTINUE
       DO 13 I=1,NO
C   CORRECTION FACTOR (TO 29.90 IN HG. AND 85DEGREES F.)
       CF(I)=(29.90/BAPRES(J))*SQRT((459.9+TEMP(I))/545.0)
C   TORQUE
       TOR(I)=10.52*LOAD(I)/12.0
C   BRAKE HP
       BHP(I)=(2.0*3.14159*TOR(I)*RPM(I))/33000.0
C   FRICTION HP
       FHP(I)=(2.*3.14159*RPM(I)*FRIC(J)*10.52)/(33000.*12.)
C   INDICATED HP
       IHP(I)=(BHP(I)+FHP(I))*CF(I)
C   CORRECTED BHP
       CBHP(I)=IHP(I)-FHP(I)
C   INDICATED THERMAL EFFICIENCY
       ETA(I)=(IHP(I)*2545.0*100.0)/(HV*LB(I))
C   MECHANICAL EFFICIENCY
       MEFF(I)=(CBHP(I)*100.)/IHP(I)
C   FUEL PER IHP
       FUIHP(I)=LB(I)/IHP(I)
C   FUEL CONSUMPTION PER CBHP
       FU(I)=LB(I)/CBHP(I)
C
C **FUEL TO AIR RATIO**
C    MEASURED ( CORRECTION FACTOR APPLIED )
       DENS=(PRESS*144.0)/(53.34*(TEMP(I)+459.7))
       HEAD=(DP(I)*62.4)/(DENS*12.0)
       VEL=0.62*(SQRT(2.*32.2*HEAD))
       FLOW=(VEL*3.14259*(0.9983**2)*15.*DENS/144.)*CF(I)
       RATIO(I)=LB(I)/(FLOW*60.0)
C AIR TO FUEL RATIO
       AF(I)=FLOW*60./LB(I)
C   FROM ORSAT ANALYSIS
       H2=0.51*CO(I)
       CH4=0.22
       TOTAL=CO2(I)+O2(I)+CO(I)+H2+CH4
       N2=100.000-TOTAL
       OXY=N2/3.76
```

```
C ZCXHY+OXY(O2)+N2(N2) = CO2(CO2)+CO)+0.3(CH4)+O2(O2)+H2(H2)+N2(N2)+2H2O
C  CARBON,OXYGEN,BALANCE
      Z(I)=(CO2(I)+CO(I)+0.22)/X
      MASS=(OXY+N2)*28.967
      FA(I)=(Z(I)*MW)/MASS
      E(I)=(FA(I)-RATIO(I))*100.0/RATIO(I)
C  TO CALCULATE HYDROGEN CARBON RATIO
      XX=X*Z(I)
      W=2.00*(OXY-CO2(I)-CO(I)/2.0-0.22)
      YY=0.83+H2*2.0+2.0*W
      HYC(I)=YY/(12.0*XX)
      FUA(I)=(12.0*XX+YY)/MASS
C
C  TO CALCULATE BRAKE MEAN EFFECTIVE PRESSURE
      ALNC=((3.14159*3.25**2)*0.375*RPM(I))/8.0
      BMEP(I)=(33000.0*BHP(I))/ALNC
      CMEP(I)=33000.*IHP(I)/ALNC
   13 CONTINUE
C
C  ** TO SORT INTO DESCENDING VALUES OF FUEL AIR RATIO**
      LIM=NO-1
   14 KNT=1
C  INITIALIZE KNT IN EVENT ALL RATIOS IN ORDER
      DO 15 I=1,LIM
      IF(RATIO(I+1).LT.RATIO(I)) GO TO 15
C  IF RATIO(I+1).GT.RATIO(I) INTERCHANGE THEM
      SORT=RATIO(I+1)
      SA=RUN(I+1)
      SB=RPM(I+1)
      SC=BHP(I+1)
      SD=FHP(I+1)
      SE=IHP(I+1)
      SF=TOR(I+1)
      SG=ETA(I+1)
      SH=MEFF(I+1)
      SI=TEM(I+1)
      SJ=FU(I+1)
      SK=FUIHP(I+1)
      SL=CMEP(I+1)
      SM=SPARK(I+1)
      SN=CF(I+1)
      SO=CBHP(I+1)
      SP=LOAD(I+1)
      SQ=COM(I+1)
      SQA=MEN(I+1)
      SQB=TS(I+1)
      SR=HYC(I+1)
      SS=FUA(I+1)
      ST=FA(I+1)
      SU=Z(I+1)
      SV=E(I+1)
      SW=AF(I+1)
      SX=CO2(I+1)
```

```
SY=O2(I+1)
SZ=CO(I+1)
SZA=LB(I)
RATIO(I+1)=RATIO(I)
RUN(I+1)=RUN(I)
RPM(I+1)=RPM(I)
BHP(I+1)=BHP(I)
FHP(I+1)=FHP(I)
IHP(I+1)=IHP(I)
TOR(I+1)=TOR(I)
ETA(I+1)=ETA(I)
MEFF(I+1)=MEFF(I)
TEM(I+1)=TEM(I)
FU(I+1)=FU(I)
FUIHP(I+1)=FUIHP(I)
CMEP(I+1)=CMEP(I)
SPARK(I+1)=SPARK(I)
CF(I+1)=CF(I)
CBHP(I+1)=CBHP(I)
LOAD(I+1)=LOAD(I)
COM(I+1)=COM(I)
MEN(I+1)=MEN(I)
TS(I+1)=TS(I)
HYC(I+1)=HYC(I)
FUA(I+1)=FUA(I)
FA(I+1)=FA(I)
Z(I+1)=Z(I)
E(I+1)=E(I)
AF(I+1)=AF(I)
CO2(I+1)=CO2(I)
O2(I+1)=O2(I)
CO(I+1)=CO(I)
LB(I+1)=LB(I)
RATIO(I)=SORT
RUN(I)=SA
RPM(I)=SB
BHP(I)=SC
FHP(I)=SD
IHP(I)=SE
TOR(I)=SF
ETA(I)=SG
MEFF(I)=SH
TEM(I)=SI
FU(I)=SJ
FUIHP(I)=SK
CMEP(I)=SL
SPARK(I)=SM
CF(I)=SN
CBHP(I)=SO
LOAD(I)=SP
COM(I)=SQ
MEN(I)=SQA
TS(I)=SQB
HYC(I)=SR
```

```
      FUA(I)=SS
      FA(I)=ST
      Z(I)=SU
      E(I)=SV
      AF(I)=SW
      CO2(I)=SX
      O2(I)=SY
      CO(I)=SZ
      LB(I)=SZA
      KNT=I
C   KNT GIVES LOCATION OF LAST INTERCHANGE
C          SUCCEEDING VALUES IN ORDER
   15 CONTINUE
      IF(KNT.EQ.1) GO TO 16
C   IF KNT=1 ALL RATIOS IN ORDER
      LIM=KNT-1
      GO TO 14
   16 CONTINUE
C
C   ** TO PRINT RESULTS **
      WRITE(6,114)
      WRITE(6,115)
      DO 17 I=1,NO
      WRITE(6,116)RUN(I),RATIO(I),RPM(I),SPARK(I),TOR(I),BHP(I),FHP(I),I
     1HP(I),CF(I),CBHP(I),MEFF(I),LB(I),FUIHP(I),FU(I),CMEP(I),ETA(I),TE
     2M(I)
   17 CONTINUE
      WRITE(6,117)
      DO 18 I=1,NO
      WRITE(6,118)RUN(I),RATIO(I),HYC(I),FA(I),FUA(I),Z(I),E(I),AF(I),CO
     1M(I),MEN(I),TS(I)
   18 CONTINUE
C   *** FOR PLOTTING RESULTS***
      IF(NO.LT.5) GO TO 24
      NN=NO
C   TO PLOT CBHP, FHP AND IHP
      RAT=RATIO(1)
      LK=0
      DIF=20.
      T=0.0
      WRITE(6,119)
      DO 19 I=1,NN
      CALL PLOTER (RATIO(I),CBHP(I),FHP(I),IHP(I),T,DIF,RAT,LK,STOIC,DD)
   19 CONTINUE
C   TO PLOT CO2,O2 AND CO
      RAT=RATIO(1)
      LK=0
      DIF=5.0
      T=0.0
      WRITE(6,120)
      DO 20 I=1,NN
      CALL PLOTER (RATIO(I),CO2(I),O2(I),CO(I),T,DIF,RAT,LK,STOIC,DD)
   20 CONTINUE
```

```
C  TO PLOT TH. EFF., TORQUE AND LOAD
      RAT=RATIO(1)
      LK=0
      DIF=2.0
      T=0.0
      WRITE(6,121)
      DO 21 I=1,NN
      CALL PLOTER (RATIO(I),ETA(I),TOR(I),LOAD(I),T,DIF,RAT,LK,STOIC,DD)
   21 CONTINUE
C  TO PLOT MECH. EFF.,CYLINDER TEMP./10.0 ,AND CBMEP
      RAT=RATIO(1)
      LK=0
      DIF=0.8
      T=20.0
      WRITE(6,122)
      DO 22 I=1,NN
      CYTEM(I)=TEM(I)/10.0
      CALL PLOTER (RATIO(I),MEFF(I),CYTEM(I),CMEP(I),T,DIF,RAT,LK,STOIC
     1,DD)
   22 CONTINUE
C  TO PLOT FUEL PER CBHP,FUEL PER IHP ANDA/F FROM ORSAT ANALYSIS
      RAT=RATIO(1)
      LK=0
      DIF=100.
      T=20.0
      WRITE(6,123)
      DO 23 I=1,NN
      AIR(I)=10.0*FA(I)
      CALL PLOTER (RATIO(I),FU(I),FUIHP(I),AIR(I),T,DIF,RAT,LK,STOIC,DD)
   23 CONTINUE
   24 CONTINUE
   99 FORMAT(I3,A6)
  100 FORMAT(F7.3,F6.2,2I3,F4.1,3A6)
  101 FORMAT(1HJ,F7.3,F6.2,2I3,3A6)
  102 FORMAT(1HJ,68HRUN SPARK REVS  TIME  AIR  DP CY TEM   CO2  O2   CO
     1  LOAD  COMMENTS)
  103 FORMAT(1HJ,79HRUN SPARK REVS  TIME  FUTEM PRES AIR  DP CY TEM   CO
     12  O2   CO   LOAD  COMMENTS)
  104 FORMAT(1H1,40X,17H CFR TEST RESULTS)
  105 FORMAT(1HL,10X,9HTEST NO. ,I3,5X,6H C.R.=,F6.2,5X,9H FUEL IS ,2A6,
     14X,22H BAROMETRIC PRESSURE =,F7.3,10X,I3)
  106 FORMAT(I2,I3,F6.0,F6.3,F4.0,F5.2,F4.0,F6.3,F6.0,F5.1,2F4.1,F5.1,3A
     16,A4)
  111 FORMAT(1HJ,I3,I5,1X,F6.0,F6.3,F4.0,F6.3,F6.0,F6.1,2F5.1,F6.1,3A6)
  112 FORMAT(1HJ,I3,I5,1X,F6.0,F6.3,F5.0,F6.2,F4.0,F6.3,F6.0,F6.1,2F5.1,
     1F6.1,3A6,A4)
  113 FORMAT(1HJ,15X,14HFRICTION LOAD=,F5.1,5H LBS.)
  114 FORMAT(1HK,40X,13H** RESULTS **)
  115 FORMAT(1HJ,25HRUN F/A(MEAS   RPM  SPARK,2X,45HTORQUE     BHP      FH
     1P      IHP     CF       CBHP,2X,8HMECH EFF,2X,21HFU/HR FU/IHP  FU/CBH
     2P,3X,23HIMEP  THER EFF CYL TEMP)
  116 FORMAT(1HJ,I3,F8.4,F8.1,I4,2X,6F8.3,F7.2,3X,2F6.3,F8.3,3X,F7.2,F8.
     12,3X,F6.0)
```

```
117 FORMAT(1HK,51H RUN F/A MEAS  H/C   F/A CAL  F/A CAL MOLES   ERROR,
   110H A/F RATIO,8X,8HCOMMENTS)
118 FORMAT(1HJ,I3,5F8.4,2F8.2,5X,3A6,A4)
119 FORMAT(1H1,10X,38HCBHP,FHP,AND IHP VERSUS FUEL AIR RATIO)
120 FORMAT(1H1,10X,37H CO2, O2 AND CO VERSUS FUEL AIR RATIO)
121 FORMAT(1H1,10X,53H THERMAL EFF., TORQUE AND LOAD VERSUS FUEL AIR
   1RATIO)
122 FORMAT(1H1,10X,53H MECH EFF, CYL TEMP/10 AND CBMEP VERSUS FUEL AIR
   1RATIO)
123 FORMAT(1H1,10X,67HFUEL PER CBHP, FUEL PER IHP AND FUEL AIR RATIO F
   1ROM ORSAT ANALYSIS )
    STOP
    END
```

```
$IBFTC PLOTER  DECK
      SUBROUTINE PLOTER(X,Y,R,S,T,DIF,RAT,LK,STOIC,DD)
      DIMENSION CHAR(99)
     DATA BLANK,PLOTY,PLOTR,PLOTS/1H ,1H*,1H+,1HX/
      IF(LK.GT.0) GO TO 1
      IF(RAT.GT.STOIC) GO TO 1
      WRITE(6,7) STOIC
    1 CONTINUE
      LK=1
      IF(RAT.LE.STOIC) GO TO 5
      IF(X.GT.STOIC) GO TO 5
      KK=(RAT-STOIC)*DD+.5
      DO 2 L=1,KK
    2 WRITE(6,3)
      WRITE(6,7) STOIC
      RAT=STOIC
    5 CONTINUE
      DO 6 JK=1,99
    6 CHAR(JK)=BLANK
      KK=(RAT-X)*DD+.5
      I=Y*DIF-T
      J=R*DIF-T
      K=S*DIF-T
      IF(I.LE.99) GO TO 10
      I=99
   10 IF(I.GT.0) GO TO 11
      I=1
   11 IF(J.LE.99) GO TO 12
      J=99
   12 IF(J.GT.0) GO TO 13
      J=1
   13 IF(K.LE.99) GO TO 14
      K=99
   14 IF(K.GT.0) GO TO 15
      K=1
   15 CONTINUE
      IF(J.EQ.I) J=I+1
      IF(K.EQ.J) K=J+1
      IF(K.EQ.I) K=I+1
      CHAR(I)=PLOTY
      CHAR(J)=PLOTR
      CHAR(K)=PLOTS
      DO 8 L=1,KK
    8 WRITE(6,3)
      WRITE(6,4)X,Y,R,S,CHAR
      RAT=X
    3 FORMAT(1HJ)
    4 FORMAT(1H ,F8.4,3F7.2,1X,1H.,99A1)
    7 FORMAT(1HJ,F8.4,23H STOICHIOMETRIC MIXTURE,10(1H.,9X))
    9 RETURN
      END
$ENTRY          POND
```

APPENDIX F

SAMPLE SET OF RESULTS

CFR TEST RESULTS

TEST NO. 5 C.R.= 9.62 FUEL IS PROPANE

** RESULTS **

RUN	F/A(MEAS	RPM	SPARK	TORQUE	BHP	FHP	IHP	CF
48	0.0574	603.0	5	20.865	2.398	0.977	3.662	1.085
49	0.0501	604.9	5	21.829	2.514	0.979	3.797	1.087
50	0.0413	594.4	5	20.514	2.321	0.962	3.569	1.087
51	0.0320	600.1	10	15.342	1.753	0.972	2.964	1.088
52	0.0254	596.6	20	8.065	0.916	0.966	2.048	1.088

CBHP	MECH EFF	FU/HR	FU/IHP	FU/CBHP	IMEP	THER EFF	CYL TEMP
2.685	73.31	1.670	0.456	0.622	128.71	27.99	803.
2.818	74.21	1.448	0.381	0.514	133.18	33.50	856.
2.607	73.04	1.193	0.334	0.457	127.41	38.22	830.
1.992	67.22	0.938	0.316	0.471	104.79	40.36	703.
1.082	52.83	0.753	0.368	0.698	72.82	34.71	535.